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THE CORRELATION OF THE ORE-BEARING SEDIMENTS OF THE KATANGA AND RHODESIAN COPPER BELT.

ANTON GRAY.

INTRODUCTION.

THE Katanga-Rhodesia Copper Belt extends in a NW.–SE. direction from Musonoi in the Belgian Congo to Bwana M'Kubwa in Northern Rhodesia In the northwestern part of this area are found the well known oxidized ores of the Katanga; Etoile du Congo, Ruashi, Luisha, Kambove, Kipushi and many others. In the southeastern part of the area are located the recently discovered sulphide ores of Rhodesia, which include the Roan Antelope, N'Kana, Mufulira and N'Changa mines. All these deposits are similar in that the principal metal mined is copper, always accompanied by varying but subordinate amounts of cobalt. Uranium ores have so far been found only in the Katanga.

The principal ore bodies of both the oxidized and sulphide type occur as bedded deposits in more or less severely folded and faulted sediments of unknown age. The ores are found in dolomites, shales and quartzites in beds which have been variously named the Série des Mines, Roan series or Bwana M'Kubwa series. Although there are a few notable exceptions in which the deposition of the ore minerals has been controlled by faulting closely associated with these beds, giving rise to vein deposits, the characteristic common to nearly all the large deposits of the area is the close association of the ores with certain strata. The

forms of the various deposits differ greatly but they are in all cases controlled, almost entirely, by the various forms assumed by the more or less contorted beds in which the copper deposition took place.

The general geology and ore deposits of parts of this district have been described in considerable detail by many geologists and engineers. Cornet [1] studied the Katanga deposits in 1890–93, and the mineralogy of the ores has been investigated and described by Buttgenbach.[2] In 1924 Fourmarier [3] published his Carte Geologique du Congo Belge on which is included the geology, exceedingly generalized, of that part of the district lying in the Katanga. More recently several excellent geologic maps of portions of the area, made under the direction of M. Robert,[4] have been published by the Comité Spécial du Katanga.[5] Van Doorninck [6] was the first to recognize the existence of the System of the Katanga, in which all the copper deposits occur, and the results of his work were published in 1928.

The geological investigation on the Rhodesian side of the border was commenced more recently. Studt [7] in 1913 gave a general description of the geology of both the Katanga and Northern Rhodesia, but the systematic and detailed examination of the Rhodesian deposits has been carried on only for the past three or four years. Bancroft [8] presented to the 15th International Geological Congress in 1929 some notes on the general

[1] Jules Cornet, "Les gisements metalliferes du Katanga," *Mem. et Publ. de la Soc. des Sci., des Arts et des Letrés du Hainaut*, 5th Ser. 8, 1896.

[2] H. Buttgenbach, "Mineralogie du Congo Belge," *M.S.R.L.* 3d Ser. 13, 1925.

[3] P. Fourmarier, "Carte Géologique du Congo Belge avec notice explicative," *Rev. Univ.*, 7th Ser. 4, 1924.

[4] M. Robert, "Le Katanga Physique." Bruxelles. M. Lamertin, rue Condenberg, 1927.

[5] Comité Spécial du Katanga, Carte du Katanga 1 : 200,000, under the direction of M. Robert and control of H. Droogmans. With notices. Bruxelles, 51 rue des Petits-Carrnes.

[6] N. H. Van Doorninck, "De Lufilische Plooiing." G. Naeff, The Hague, 1928.

[7] F. E. Studt, "The Geology of Katanga and Northern Rhodesia," Geol. Soc. So. Afr., 1913.

[8] J. A. Bancroft and R. A. Pelletier, "Notes on the General Geology of Northern Rhodesia," Int. Geol. Con., 15th Session, 1929. Reprinted in *Mining Mag.*, London, Dec., 1929, Jan., Feb., March, 1930.

geology of Northern Rhodesia, in which he described several of the ore deposits, and Gray and Parker [9] in the same year described the geology and ore deposits of the N'Kana Concession. Bateman [10] has given an excellent summary of the geology of the Rhodesian copper district, and a detailed discussion of the ores.

All the authors enumerated above have confined their attention to a particular part of the copper belt. The Belgian geologists were interested principally in the Katanga, and the more recent work in Rhodesia has been confined largely to the vicinity of the N'Kana and Rhodesian Congo Border concessions. Nearly all the geologists working in Rhodesia have speculated on the relationship existing between the Katanga and Rhodesian deposits, and on possible correlations of the beds which contain them. However, dissimilarity of the ore-bearing sediments in the various parts of the district, combined with the flat, heavily forested topography, with its deep mantle of soil and great scarcity of outcrops, has made the correlation of rocks over the district a difficult task. It is only recently that sufficient data have been gathered to make such a correlation possible.

The present paper gives the results of investigation of many of the deposits and much of the data available at the present time. The writer desires to acknowledge his indebtedness to the work of the men enumerated above and to many others. Much of the knowledge we now have of Rhodesian geology is due to the work of Dr. Bancroft and his assistants. The investigation of the rocks and ore deposits of the Katanga was made possible to the writer through the courtesy of the Comité Spécial du Katanga and the Union Minière du Haut Katanga. Particular thanks are due for the courtesy and interest shown by Messrs. Schuiling and Dubois, chief geologists of the Union Minière and Comité Spécial respectively, who spent considerable time and gave freely of their knowledge during this work.

[9] Anton Gray and R. J. Parker, "The Copper Deposits of Northern Rhodesia," *E. and M. J.*, vol. 128, 1929.

[10] Alan M. Bateman, "The Rhodesian Copper Deposits," *Canadian Min. and Met. Bull.*, pp. 477–513, April, 1930. "The Ores of the Rhodesian Copper Deposits," ECON. GEOL., vol. 25, pp. 363–418, June, 1930.

GENERAL GEOLOGY OF THE COPPER BELT.

The entire area of the copper district is characterized by slightly rolling topography, broken here and there by ridges or hills composed of the more resistant rocks. The average elevation of the ground is 1200 meters, and the higher portions represent an old peneplain, re-elevated in comparatively recent times, and upon which has just commenced a new cycle of erosion. Rock weathering exists to exceptional depths, and the soil covering attains a thickness of as much as 25 meters, averaging between 10 and 15 meters. Except for the swampy areas along the streams the ground is covered by forest.

Such topographic conditions make geological work difficult. Outcrops of the resistant rocks are scarce, and the more easily weathered sandstones, shales, and limestones are rarely found at the surface. The sedimentary succession, thicknesses, and structures have been worked out from the information gained from small outcrops, prospecting pits, and boreholes. As most of this work has of necessity been concentrated near known copper-bearing rocks, detailed knowledge of both the rock succession and structures, such as might well be gained from even a preliminary reconnaissance in a more mountainous region, is still lacking in this district.

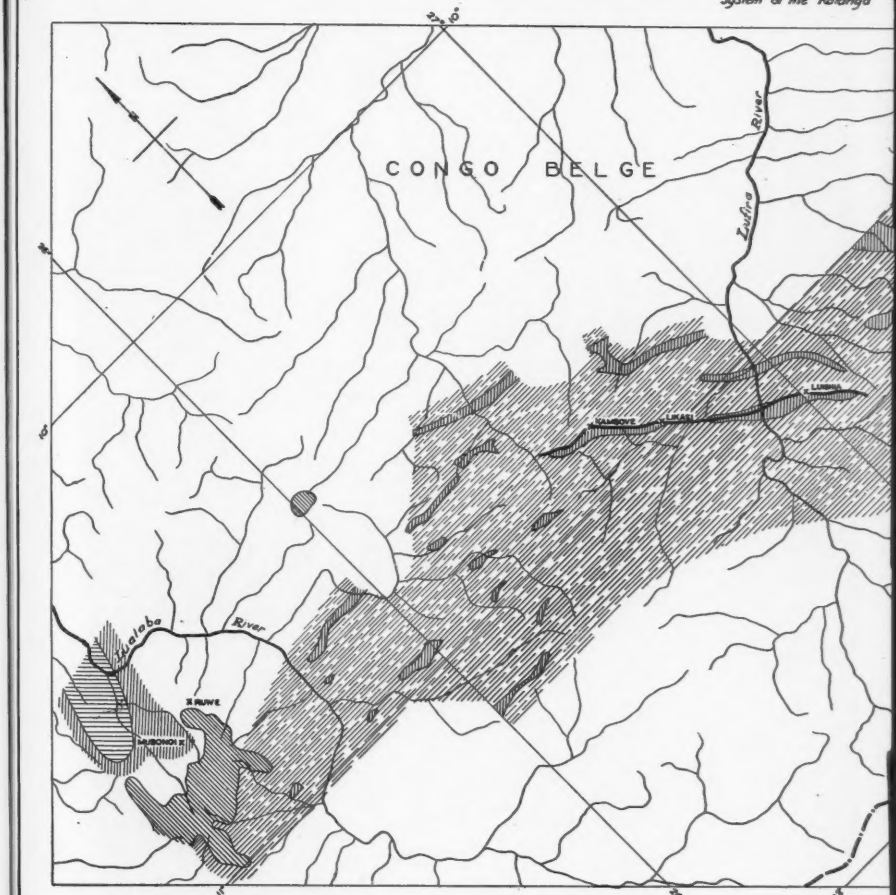
The accompanying map (Fig. 1) has been compiled from many sources, but principally from the maps of the Comité Spécial,[11] Union Miniére,[12] and Rhodesian Selection Trust.[13] The names of the formations used are those adopted in the present paper.[14] No attempt has been made on this map to distinguish between the two systems that form what is known as the "Basement" complex, nor between areas of older and younger granites. Only the principal zones of faulting have been shown, and both the scale used and the lack of detailed information have made it

[11] Comité Spécial du Katanga, *op. cit.*

[12] Union Minière du Haut Katanga, Carte Géologique de la Zone du Cuivre, issued to members of the 15th Int. Geol. Congress.

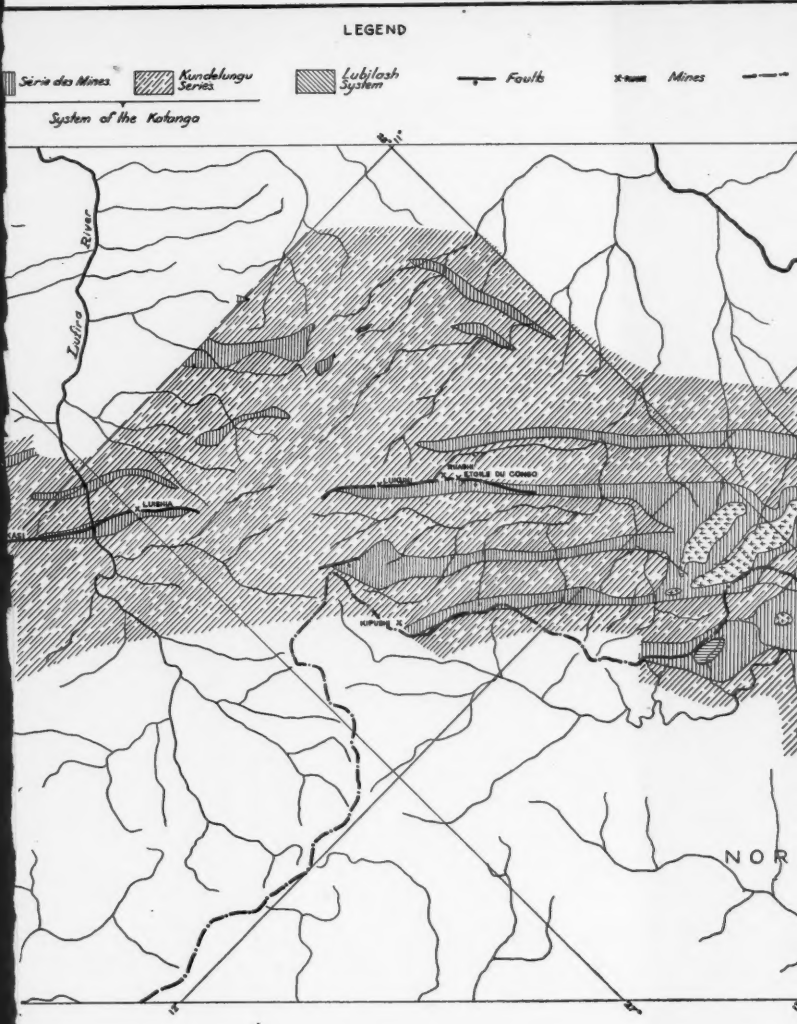
[13] Published by Anton Gray and R. J. Parker, *op. cit.* See also papers by Alan M. Bateman, *op. cit.*

[14] For a comparison of the various local names for these formations, and the names used in the publications enumerated in the introduction, see Fig. 2.



Base compiled from:
Provisional map of the Katanga, 1:500,000, issued by the Comité Spécial du Katanga;
Provisional map of Northern Rhodesia, 1:1,000,000 issued by the Northern Rhodesia Government.
Drawn by C.H. Stoberg.

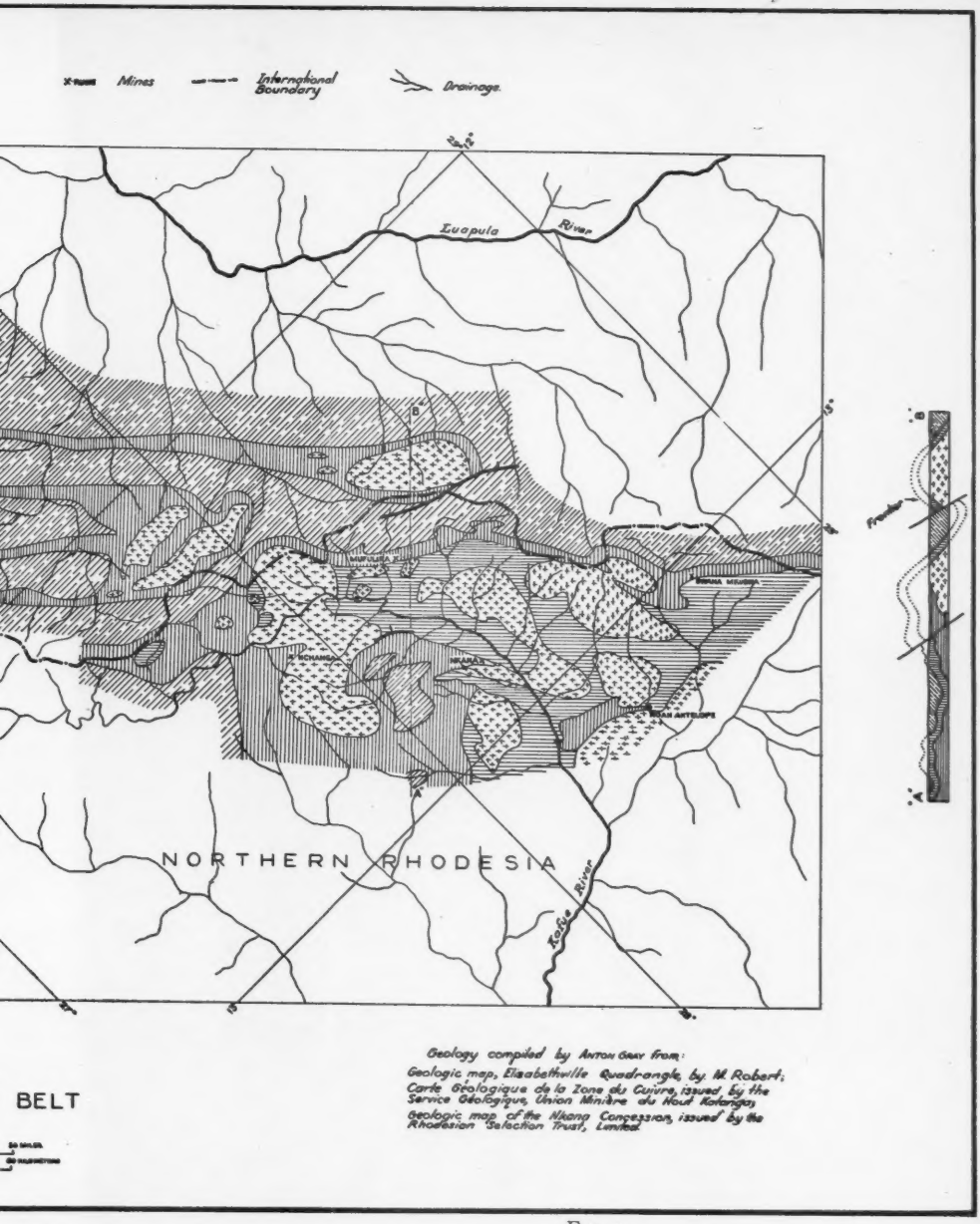
KAT



GEOLOGIC MAP
of the
KATANGA-RHODESIA COPPER BELT

MAY 1930

SCALE 1:1,000,000



Geology compiled by Anton Geav from:
Geologic map, Elisabethville Quadrangle, by M. Robert;
Carte Géologique de la Zone du Cuivre, issued by the Service Géologique, Union Minière du Haut Katanga;
Geologic map of the Nkana Concession, issued by the Rhodesian Selection Trust, Limited.

FIG. 1.

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necessary to map the two series of the System of the Katanga as units, taking no account of their various sub-divisions.

The "Basement" Schists.

The oldest rocks of the area are the ancient schists, gneisses and granite, which form the floor, now warped and distorted. upon which the younger copper-bearing sediments were laid down. This ancient complex consists of three distinct groups of rocks, probably all of pre-Cambrian age. The oldest of these is the Lufubu system, highly metamorphosed and extremely contorted sediments which, within the district under consideration, are exposed only in a few places. The Muva system, lying unconformably above the Lufubu schists, is also composed of very ancient sediments, some of the members of which are, fortunately, very distinctive and easily recognizable rocks. The quartzites of this system, particularly, are resistant rocks and in many places form well exposed ridges. Their composition, textures and weathering effects are such that they are not to be confused with any of the younger sediments.

Both these systems, before the formation of the System of the Katanga, were intruded by large masses of granite. From these rocks was derived the material of which the sediments of the System of the Katanga were formed.

System of the Katanga.

Overlying this ancient complex is a thick succession of sediments which Van Doorminck [15] (Fig. 2) has called the System of the Katanga. No fossils have been found in these beds, and their age is as yet unknown.[16] In the central part of the Katanga copper district the base of this system is not exposed, but it is found in the neighborhood of Musonoi, along the Rhodesia-Congo border, and in the copper district of Rhodesia.

[15] N. H. Van Doorninck, *op. cit.*

[16] Alan M. Bateman, "The Rhodesian Copper Deposits," *op. cit.*, p. 11. It is stated in a footnote that Prof. Adolph Knopf estimates the age of the Katanga radium ores, contained in these rocks, as 610 million years, therefore, of late pre-Cambrian age.

The basal beds consist of a succession of conglomerates, arkoses, feldspathic sandstones, shales and thin beds of dolomite, some 350 meters in thickness. These beds are in most cases separated from the underlying Muva and Lufubu systems by a marked unconformity.

The dolomites of the lower Roan become thicker towards the

CORRELATION OF THE GEOLOGIC NOMENCLATURE USED IN RHODESIA AND THE KATANGA

P. FOURMARIER	M. ROBERT	VAN DOORNINCK	BANCROFT. 1932	U.M.H.K. 1932	GRAY 1933	NOMENCLATURE ADOPTED IN PRESENT PAPER	
SYSTÈME du LUBILASH-LUALABA	SYSTÈME du LUBILASH-LUALABA	LUBILASH SYSTEM	NOT PRESENT IN NORTHERN RHODESIA	SYSTÈME du LUBILASH	NOT PRESENT IN KATANGA CONCESSION.	LUBILASH SYSTEM	TRIASSIC.
							UNCONFORMITY.
SYSTÈME du KUNDELUNGU (Red Kundelungu) and SÉRIE SCHISTO CALCAIRE (Gilded Kundelungu in the Katanga)	SYSTÈME du KUNDELUNGU: Kundelungu Supérieur	Plateau Arkose Series	KUNDELUNGU SERIES.	SYSTÈME du KATANGA, GROUPE du KUNDELUNGU: Kundelungu Supérieur	Purple Quartzites	KATANGA SYSTEM, KUNDELUNGU SERIES: Upper Kundelungu Group.	
	Kundelungu Inférieur	Kafubu Series; Tillite of the Katanga		Kundelungu Inférieur	Mukondo Series	Lower Kundelungu Group.	
SÉRIE METAMORPHIQUE	SYSTÈME SCHISTO DOLOMITIQUE CHERTEUX	SYSTEM of the KATANGA: Muvashia Series	BWANA MKUBWA SERIES: Upper	SYSTÈME du KATANGA, GROUPE INFÉRIEUR ou ROAN: Série des Mines	Chimfwasa Series	SYSTEM of the KATANGA, KUNDELUNGU SERIES: Muvashia Group.	
		Série des Mines	Middle	Série des Mines	Upper Roan Series	SÉRIE DES MINES: Upper Roan Group.	COPPER DEPOSITS OF THE KATANGA.
			Lower	? ?	Lower Roan Series	Lower Roan Group.	COPPER DEPOSITS OF N. RHODESIA.
							UNCONFORMITY.
SÉRIE CRISTALLINE et CRISTALLOPHYLLIENNE	SYSTÈME PRIMAIRE INFÉRIEUR		BROKEN HILL SERIES	SOCLE CONTINENTAL ANCIEN: SYSTÈME PRIMAIRE INFÉRIEUR	MUVA SCHIST	MUVA SYSTEM	
			?—?—				UNCONFORMITY.
	SYSTÈME RÉPUTÉ ARCHÉEN		BASEMENT SCHIST SERIES.	SYSTÈME RÉPUTÉ ARCHÉEN	LUFUBU SCHIST	LUFUBU SYSTEM	

COMPILED BY ANTON GRAY FROM THE FOLLOWING INFORMATION

FIG. 2.

top, and pass upward without a break into the upper Roan group, composed principally of dolomites and dolomitic shales with some interbedded sandstones. These beds contain the dolomites of the Série des Mines, which in the Katanga carry the great copper deposits.

Lying above the upper Roan, but conformable with it, is the M'Washia group composed of some 400 to 600 meters of shales with local dolomitic beds and several fairly persistent sandstone horizons. The base of this group is marked by a formation, not

over 5 meters in thickness, composed of alternating chert and silicious oölite. The uppermost beds consist commonly of fairly distinctive feldspathic sandstones, which at some places in the southern part of the area are replaced by a banded silicious iron stone.

These three groups I have called the Série des Mines. This name was first used in referring to the ore-bearing dolomites of the Katanga, but as no unconformity has been found between these rocks and those overlying and underlying them I have, in agreement with Schuiling and Dubois,[17] extended the name to cover the entire series.

Overlying the Série des Mines, and attaining at places a thickness as great as 4,000 meters, is the Kundelungu series. There is apparently no unconformity between these rocks and the underlying Série des Mines, at least within the area of the copper belt. Bancroft,[18] however, has found that the Kundelungu beds extend over a greater area than the Série des Mines, the basal conglomerate at places lying directly on the ancient schists. These beds represent, therefore, a transgressive overlap in the sedimentation of the original basin in which the System of the Katanga was laid down.

The basal formation of the Kundelungu series, the so-called Tillite of the Katanga, is a very distinctive and persistent horizon of fluvio-glacial shales and conglomerates. This is followed by a succession, almost identical in Rhodesia and the Katanga, of dolomite, dolomitic shales, sandstones and feldspathic quartzites, which make up the lower Kundelungu. Then, with no disconformity, comes the "Petit Conglomérat" of the Kundelungu, a formation very similar to the basal conglomerate of the series but much thinner, followed by relatively thin beds of limestones, shales and sandstones and, at places, the feldspathic sandstones known as the "Plateau" arkoses.

All these rocks participated in the movements that caused the complicated folding and faulting now found throughout the dis-

[17] H. J. Schuiling, chief geologist of the Union Minière du Haut Katanga, and M. Dubois, chief geologist of the Comité Spécial du Katanga.

[18] Personal communication.

trict. Lying unconformably and almost horizontally upon the eroded surface of these folded and considerably metamorphosed beds are the lower Mesozoic sediments of the Lubilash system.

The Lubilash beds have been almost entirely removed from the area of the copper belt, leaving exposed the truncated edges of the beds of the System of the Katanga, and over considerable area the underlying schists and older granites. Following, or accompanying, the folding of the beds there was an intrusion of younger granite which, although the area has been deeply eroded, has been exposed only in a few places. The copper deposits of the district are in all probability associated with this granite.

Although this area has been described as a peneplain, only the higher parts of the present topography really represent this ancient surface. In comparatively recent times there has been a rejuvenation of the drainage, probably caused by vertical uplift accompanied by little, if any, folding, and the present topography is in a very youthful stage. A new cycle of erosion has commenced, but has not yet had time to do more than entrench a few of the old channels.

THE SÉRIE DES MINES.

There has never been any serious question of the correlation of the Kundelungu series in Rhodesia and the Katanga. The succession of beds, and particularly the fluvio-glacial conglomerates, are so distinctive that they were recognized in the Rhodesian part of the district almost as soon as geologic work commenced. Since then the basal conglomerate of the series has been traced fairly continuously from the vicinity of Elisabethville into the Mufulira syncline. The principal difficulties have arisen in the correlation of the beds lying below the Kundelungu but above the Muva system. The difficulty arose from two main causes. First, the basal beds of the Katanga system are not exposed in the central part of the Katanga, where most of the prospecting and mining work has been carried out. Second, the dolomites of the Série des Mines rarely, almost never, outcrop in the Rhodesian part of the district, and have only recently been exposed by drilling and prospect pitting.

Fig. 3 gives a comparison of the succession of the Katanga system near Elisabethville in the Katanga, and Mufulira in Rhodesia. The Elisabethville succession was tabulated by Du-

COMPARISON OF THE SYSTEM OF THE KATANGA IN KATANGA AND RHODESIA.

SECTION THROUCH THE SYSTEM OF THE KATANGA IN THE VICINITY OF ELISABETHVILLE, ACCORDING TO DU BOIS.		SECTION THROUGH THE KATANGA SYSTEM IN THE VICINITY OF MUFULIRA.	
FORMATION.	THICKNESS (Metres) Not present.	FORMATION.	THICKNESS. (Metres). Not present.
SYSTEM OF THE LUBILASH		LUBILASH SYSTEM	
SYSTEM OF THE KATANGA		KATANGA SYSTEM	
UPPER KUNDELUNGU	2000±	UPPER KUNDELUNGU	2000±
Shales, more or less sandy	——	Arkoses, purple Quartzites & Shales	——
Calcaire Rose	5-10	Calcaire Rose.	10±
Shales	0-10	Shales	Less than 50
Petit Conglomerat	10-30	Petit Conglomerat	At least 30
LOWER KUNDELUNGU	1500±	LOWER KUNDELUNGU	2000
Feldspathic Sandstone	0-30	Feldspathic Sandstone	——
Shales	——	Calcareous sandy Shales	——
Calcareous Sandstone	——	Shales	——
Calcareous Shales	——	Kakontwe Limestone	100±
Calcaire de Kakontwe	50-100.	Shales	150±
Shales	0-50.	Basal Conglomerat	
Grand Conglomerat	100-400.		
MWASHIA	300-500	MWASHIA	400-600
Feldspathic Quartzite	10-50.	Feldspathic Sandstone	15±
Black Shales	100-400.	Black and various banded Shales with interbedded Sandstones	——
Green dolomitic Shale		Chert and Oolites	Not over 5.
Chert and Jasper	1-2		
Siliceous Oolites	1-2		
DOLOMITES of the SÉRIE DES MINES (Base unknown)	200-400.	UPPER ROAN	550-600
		Dolomites and dolomitic Shales with interbedded Sandstones	——
		LOWER ROAN	350+
		Interbedded Shales, Sandstone and Dolomite.	175.
		Feldspathic Sandstone, Grit and Conglomerate	175
		MUVA SYSTEM	?

FIG. 3.

bois,[19] and that for Rhodesia has been worked out independently by the Rhodesian Selection Trust geologists.

Dubois, Van den Brande and Schuiling have found no disconformity between the M'Washia and the dolomites of the Série des Mines in the Katanga. Although the structure in the vicinity of the mines is often so complicated by faulting that the relation

[19] M. Dubois, tabulated at the request of the author.

between these rocks is uncertain, they have been near M'Washia [20] and other places exposed in unbroken anticlines. At these places, the Série des Mines dolomites are found to underlie the M'Washia sediments without a break.

The rocks of the Série des Mines that lie below the ore-bearing dolomites, although unexposed in the vicinity of the principal Katanga mines, have been recognized by the writer at two places in the Congo: (1) At the falls of N'Zilo; and (2) on the Rhodesian-Congo frontier.

At the Falls of N'Zilo on the Lualaba river, near Musonoi, there is an excellent exposure of Muva quartzite. The Lualaba river has cut a deep gorge through the rock and this correlation does not rest upon the examination of an isolated small outcrop, but on a large area of the comparatively fresh rock. The composition, texture, structure, and weathering effects are so typical that there is no doubt about the identification in the writer's mind, nor in the minds of the other Rhodesian geologists who have seen either the outcrops or specimens. Just upstream from the main gorge, east of the Muva and striking across the river at about N. 20 E., may be seen outcrops of conglomerate and feldspathic sandstones. As in Rhodesia, the pebbles of the conglomerate are largely made up of Muva quartzite. They are for the most part well rounded and form over 75 per cent. of the rock. The matrix is coarse and feldspathic. The feldspathic sandstones are identical with those found in the lower Roan in Rhodesia. Conglomerate beds appear interbedded in the sandstones, and above them, farther up the river, Gutzeit [21] has found outcrops of sandy shales.

These rocks Gutzeit has traced southward to a point west of Musonoi where they dip about 60 degrees to the east, that is, under the dolomites of the Série des Mines that contain the copper deposits of Musonoi and Kolwesi. He also states that he is able to detect no break in the succession and no faults, and that he considers these conglomerates and sandstones to form the base of the Série des Mines.

[20] M. Van den Brande, geologist of the Comité Spécial du Katanga. M. Dubois and Schuiling, personal communications.

[21] G. Gutzeit, geologist of the Union Minière du Haut Katanga, personal communication.

The writer, together with Mr. R. J. Parker, examined these rocks and the ore-bearing dolomites of Musonoi, and are certain that they represent not only the base of the Katanga system, but correspond to what has been called in Rhodesia the lower Roan. At this place the base of the System of the Katanga rests unconformably upon the Muva system, and the succession is essentially the same as in Rhodesia, that is, conglomerates, feldspathic sandstones and sandy shales passing upward into copper-bearing dolomites. Both Gutzeit and Schuiling[22] are certain that the ore-bearing rocks of Musonoi are the dolomites of the Série des Mines.

On the Rhodesia-Congo border, from a point just east of Mufulira almost to Kipushi, there are exposures of the conglomerates and feldspathic quartzites lying at the base of the System of the Katanga. Where the frontier crosses longitude 27° 40′ E. these conglomerates have been mapped by Robert[23] as Kundelungu. More recent investigations carried out by the geologists of the Rhodesian Congo Border Concessions and by the writer, however, have shown that the basal conglomerate of the Kundelungu lies above this conglomerate and is separated from it by a considerable thickness of Roan and M'Washia sediments.

On the frontier just east of Mufulira Timmerhans[24] has mapped the basal Roan conglomerate and overlying copper-bearing quartzites as M'Washia and believes that the copper deposits of Rhodesia are contained in the upper M'Washia sediments.[25] A considerable amount of prospect pitting, however, has disclosed, lying above this conglomerate, a normal succession of lower Roan, upper Roan and M'Washia beds, with the copper contained almost entirely in the lower Roan, very little in the upper Roan, and none in the M'Washia.

22 Personal communications.

23 M. Robert, Comité Spécial du Katanga, *op. cit.*, Feuille Tshinsenda.

24 M. Timmerhans, geologist for the Union Minière du Haut Katanga. Map and correlation table issued to members of the 15th Int. Geol. Congress.

25 Robert, on his Carte Géologique du Katanga, printed in November, 1929, has followed Timmerhans in placing the ore-bearing strata of Rhodesia in the M'Washia, and in mapping the basal Roan at N'Zilo as Kundelungu. The above criticism of Timmerhans' work applies equally to Robert's use of it in his compilation.

In Rhodesia the succession of the lower series of the Katanga system, or Série des Mines, has been worked out in detail, principally in the vicinity of Mufulira mine. The series is found to have a maximum thickness of about 1800 meters and has been divided into three groups, called respectively the lower Roan, upper Roan and M'Washia.

The lower Roan consists of from 350 to 600 meters of alternating conglomerates, arkoses, sandstones, and sandy shales with a few thin beds of dolomite. Where present, the basal conglomerate varies from 0 to 200 meters in thickness. The pebbles and boulders are composed in large part of the rock lying immediately beneath it, being at some places almost all Muva quartzite, at others the older granite. The pebbles form a large percentage of the rock, and although variable in size, they are mostly well rounded. The matrix is a coarse, feldspathic sand.

Above the basal conglomerate individual horizons of the group are difficult to trace, but everywhere the main characteristics are the same. At the base lie the feldspathic grits, with or without a basal conglomerate. Above these come a succession of feldspathic sandstones, alternating with beds of argillaceous sandstone, a few shale beds and some dolomite, with lenses of conglomerate occurring at irregular intervals. These beds have the characteristics of shallow-water, continental deposits.

Towards the top these sediments become finer and more dolomitic, and finally grade into the dominantly dolomitic beds of the upper Roan. These beds are exposed in very few places in Rhodesia, but test pits and boreholes show the group to be composed of thin beds of white or gray dolomite, dolomitic shales and a few beds of sandstone. The group is probably not over 600 meters thick.

At or near the surface these rocks appear as talc schists and more or less cellular, banded cherts. At one place banded quartzite, the bands representing original bedding planes, was found to pass at a depth of less than 10 meters into a massive gray dolomite. Many of these beds, even at great depth (200 to 300 meters), are very talcose.

The dolomites become sandier towards the top and in these

sandstones are found, locally, several lenses of what appears to be an intra-formational conglomerate. The exact horizon of these conglomerates has not yet been determined, but it is thought that they lie just below the chert and oölite formation which is here taken as the base of the M'Washia. This formation is apparently not over 5 meters thick and is overlain by the shales and sandstones, having a maximum thickness of 600 meters, that form the M'Washia group.

The lower part of the M'Washia is dominantly shaley. The lower shales are apt to be well banded, but higher in the group they become more massive and are often black and graphitic. Towards the upper part of the group thin layers of sandstone begin to appear, interbedded with black shales. The sand grains in these beds, unlike those of the lower Roan, are in large part considerably rounded and often have a frosted appearance. Individual layers of these sands may be less than one centimeter, or as much as 5 meters in thickness, but near or at the top of the group there is a fairly persistent feldspathic sandstone horizon that may attain a thickness of 15 meters. At some places this horizon contains a silicious banded ironstone. The M'Washia group is overlain conformably by the basal formation of the Kundelungu.

From the foregoing it will be evident that the succession of the Série des Mines is essentially the same in Rhodesia as in the Katanga. Although individual beds are difficult or even impossible to trace, the series may be divided over the entire copper belt into three groups. The lower of these is essentially sandy and conglomeratic. It is well exposed in the southeastern part of the area near the Rhodesian copper deposits, and in the northwestern part of the area near Musonoi.

The middle group is best exposed in the Katanga. It is essentially dolomitic and includes the ore-bearing dolomites of the Katanga. It appears to be of very little economic importance in Rhodesia, but is known to contain copper. The upper, or M'Washia group, is probably equally well exposed throughout the district and contains some of the Katanga copper mineralization. It contains distinctive beds which have formed some of the

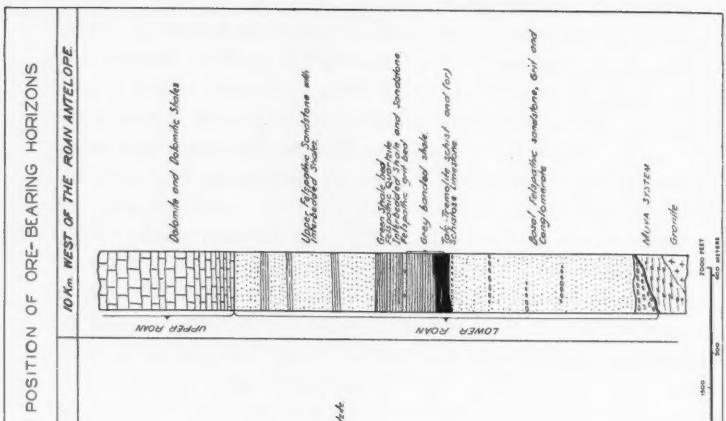
SECTIONS THROUGH THE LOWER SÉRIE DES MINES SHOWING POSITION OF ORE-BEARING HORIZONS
MUFULIRA
CHAMBISHI
10 Km. WEST OF THE ROAN ANTELOPE
UPPER ROAN
LOWER ROAN
Dolomite
Fourth Feldspathic Quartzite
Blue Shale
Third Argillaceous Sandstone
Third Feldspathic Quartzite with beds of Dolomite
Second Argillaceous Quartzite
Mertor Quartzite (part)
Lower Argillaceous Quartzite
Second Feldspathic Quartzite with PART-CONGLOMERATIC
Intermediate Argillaceous & Feldspathic Schists
Lower Feldspathic Quartzite with SECOND ORE HORIZON
Footwall grits and Quartzites
MUVA SYSTEM
Granite
Gabbro
Dolomite
Sandy talc schist
Dolomite
Schist and Quartzite
Upper Quartzite
Ore Shale
Footwall Quartzite
Granite
Dolomite and Dolomitic Shales
Upper Feldspathic Sandstone with interbedded Shales
Green Shale and Feldspathic Quartzite
Feldspathic grit and Sandstone
Grey banded shale
Talc Tremolite schist and (or) Tremolite Limestone
Basal Feldspathic sandstone, Grit and Conglomerate
MUVA SYSTEM
Granite
Ore Bearing Horizons
1500
1000
500
0
SCALE FEET
500 METRES

FIG. 4.

marker horizons in the correlation of the various faults of the area.

There is nowhere in the area any evidence of unconformity between the Série des Mines and the Kundelungu series. Local disconformity between the two is indicated by a few pebbles of the M'Washia oölite which have been found in the Kundelungu conglomerate, but this, in view of the evident overlap of the Kundelungu beds, can hardly be considered as evidence of any considerable unconformity. Certainly there have never been found at any place known to the writer any discrepancies in the stratification of the two series, and in a well exposed section near Kambove the M'Washia shales may be observed to pass, without a break, into the Kundelungu conglomerate. Therefore, it is considered that these two series represent a single system of strata, the System of the Katanga, separated by marked unconformities from the underlying basement schists and overlying Lubilash system.

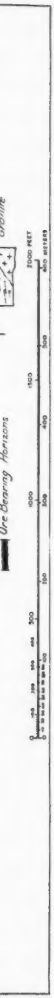

FIG. 4.

ORE DEPOSITS.

Stratigraphic Position of the Rhodesian Ores.

The ore deposits of the Rhodesian copper mines are found in the lower Roan group of the Série des Mines. Fig. 4 shows sections through the lower part of the Série des Mines at Mufulira, Chambishi and a prospect 10 kilometers west of the Roan Antelope mine. It will be seen that although the lower Roan differs in thickness and details of succession at all these places, the principal horizons may be correlated. In all cases there is a lower formation made up principally of feldspathic quartzite and grit, with interbedded conglomerates. This is thickest west of the Roan Antelope, but at Chambishi it appears to have been largely removed by an intrusion of granite.

Above this formation, shales and dolomites appear interbedded with quartzites, and it is just under or in the lower of these shaley members that the ores are found. At Chambishi and Roan Antelope the ore is contained in the more or less dolomitic sandy shale just overlying the basal quartzite, and this is true also of N'Kana and part of the N'Changa ore body. At Mufulira the ore is

found at three horizons, principally in the feldspathic quartzites just beneath shale or dolomitic beds. At Bwana M'Kubwa the ore horizons are similar to Mufulira, and in a part of the N'Changa ore body the copper is also found in feldspathic quartzite underlying a shaley bed.

Although these ores are contained in different rocks it is certain that they all occur at nearly the same horizon, that is, just above the massive basal quartzites, at the horizon where the shales and dolomites first begin to appear in the series.

Above the ores at all the mines there is a similar succession of interbedded sandstones, shales and more or less dolomitic sandy beds, overlain by the dolomites and dolomitic shales of the upper Roan.

Although it is true that all the known ore bodies of commercial value in the Rhodesian district are found at practically the same horizon, copper mineralization has been found at other horizons in the Série des Mines, and also in the overlying Kundelungu. The Série des Mines beds have been traced continuously from Mufulira to Bwana M'Kubwa, and at the Lufua prospect, 35 kilometers southeast of Mufulira, copper has been found in a horizon considerably above that which contains the ore bodies at Mufulira and Bwana M'Kubwa.

One of the columns in Fig. 5 shows the position of this mineralization. The lower Roan succession at this place is well exposed and is practically the same as at Mufulira. The lower part of the upper Roan does not outcrop, but exposures of the M'Washia and Kundelungu beds are found above the unexposed portion of the series. At a horizon just below the M'Washia a considerable amount of malachite float was found in a small swamp. This led to the digging of trenches and the sinking of several boreholes, which exposed copper mineralization in the dolomites lying just below the M'Washia, that is, in the upper part of the upper Roan.

The structure at this place is fairly simple, and it was an easy matter to determine the sequence of the beds and their relative position in the column. The mineralization here is almost exactly similar to that found in the mines of the Katanga. The

drillholes [26] exposed more or less massive fine-grained dolomite, carrying low-grade chalcopyrite mineralization. Near the surface some of this chalcopyrite is altered to chalcocite, but most

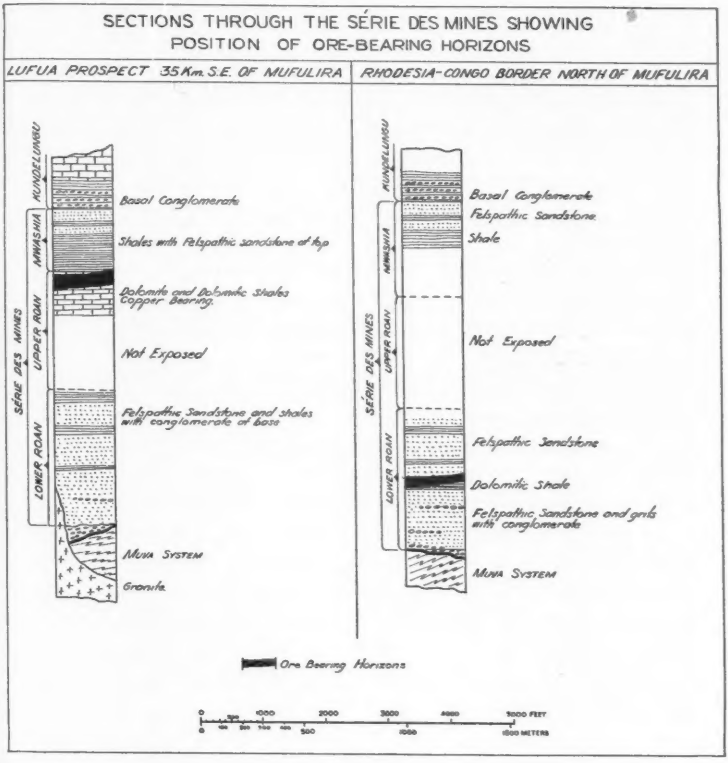

FIG. 5.

of the copper is in the form of malachite, and the values have been considerably enriched. The small amount of ore found is present as a very superficial concentration of oxidized copper con-

[26] Examination of these cores was made possible through the courtesy of the Bwana M'Kubwa Copper Mining Co., Ltd.

tained in the very much altered silicified dolomite. This is the only prospect in the Rhodesian part of the copper belt which not only closely resembles the Katanga deposits in type, but is also found to lie in the same horizon which contains the mines of the Congo.

In the same Fig. 5, for the purpose of comparison, has been shown the stratigraphic column of the beds lying just north of Mufulira along the Rhodesian-Congo border. On the eastern limb of the Mufulira syncline copper-bearing outcrops have been traced for over 30 kilometers. The copper is found in the same horizon as that which contains the Mufulira ore body, whereas the upper Roan and lower part of the M'Washia beds are not exposed along this strike. The upper M'Washia and basal beds of the Kundelungu are found at a number of places. The stratigraphic sequence here is found to be almost exactly similar to that at the Lufua prospect.

Sections from these two places show, better than any other illustrations that can be found in the area, the relative stratigraphic positions of the principal ore bodies of Rhodesia, illustrated by the Rhodesian-Congo Border section, and of the Katanga deposits, illustrated by the Lufua prospect section.

As yet of no importance economically, but a matter of considerable interest, is the fact that low-grade chalcopyrite mineralization has been found in the Mufulira basin in the Kakontwe limestone, lying just above the basal conglomerate of the Kundelungu. Where this mineralization occurs the rock is considerably fractured and brecciated by bedding faults, presumably caused by the intense folding.

Stratigraphic Position of the Katanga Ores.

The ore-bearing dolomites of the Série des Mines lying conformably just below the M'Washia beds have been divided by Schuiling into the following members:

Upper Dolomite	50–200 meters	
Dolomitic Schist	30– 80 "	
Cellular Quartzite	10– 20 "	
Banded Cherty Quartzite ...	4– 10 "	
Talcose Dolomite	10–200 "	with maximum thickness unknown.

In the vicinity of Musonoi, Gutzeit [27] finds that the upper dolomite is replaced by: (*a*) Silicified quartzite; (*b*) sericitic sandstone; (*c*) banded shales; (*d*) a thin bed of banded quartzite; (*e*) shales. The last two members are in many cases missing.

The succession at Musonoi is therefore more nearly similar to that in Rhodesia than Schuiling's succession worked out in the vicinity of Panda and Elisabethville. The upper part of the upper Roan in Rhodesia is in places sandy. The talcose sandstone in this horizon at Mufulira Mine is exactly similar to that exposed in the pits at Musonoi.

The principal ore bodies of the Katanga are found in these dolomites of the Série des Mines. It is to be noted that the names of these members have been derived from the appearance of the rocks at the surface, where they are often leached and silicified, resembling slightly, if at all, the dolomites from which they have been derived, which appear only in the boreholes.

At Chituru Mine, near Likasi, the ore-bearing dolomite is immediately overlain conformably by the chert and oölite beds of the M'Washia, and this is followed by the M'Washia beds and the overlying basal conglomerate of the Kundelungu. The beds underlying the ore-bearing dolomite are not exposed, but the position of this dolomite just beneath the M'Washia is clear. This occurrence is almost exactly similar in position to the much smaller deposit at Lufua prospect, except that the mineralization, in part, extends up into the M'Washia.

The ore-bearing dolomites of the Katanga lying just below the M'Washia group correspond therefore to the dolomites of the upper Roan. It is this horizon which contains the ore deposits of Etoile du Congo, Ruashi, Lukuni, Luishia, Likasi, Kambove and Musonoi.

Comparison of Rhodesian and Katanga Deposits.

With one notable exception, the copper deposits of the Katanga are oxidized ore bodies lying very close to the surface. Malachite is the principal ore mineral, although, particularly at depth, sul-

[27] G. Gutzeit, personal communication.

phides are found at many of the mines. The principal ore bodies of Rhodesia, on the other hand, are sulphide deposits that extend to considerable depths below the surface. Bwana M'Kubwa is an exception to this, but at Bwana M'Kubwa the beds are much more dolomitic than is usual in the Rhodesian district.

The reason for this difference is evident. In both cases the ores have been derived from primary deposits consisting principally of disseminated chalcopyrite, accompanied by more or less bornite. Where this primary deposition took place in dolomitic rocks supergene enrichment has concentrated the copper from the eroded part of the beds at or near the surface in the form of carbonate minerals. Where the primary copper was contained in the less dolomitic and more porous beds of the lower Roan the same supergene processes have resulted in a sulphide concentration lying well below the present water table. The original copper-bearing rock near the surface has been in most cases thoroughly decomposed and leached. This is the principal reason why the Katanga copper deposits were developed so long before the Rhodesian deposits were discovered.

The reasons why the original copper deposition took place in the lower Roan in part of the belt, and in the dolomites of the upper Roan in another part, are imperfectly understood. From an inspection of the accompanying map and sections, however, certain facts are evident. Where contained in the lower Roan, the copper mineralization always occurs in or just below the lower impervious beds of the Série des Mines. One thing is evident from an examination of these deposits, and that is, the mineralizing solutions penetrated through the porous or fractured beds until their course was dammed by beds they could not penetrate. Thereafter their course was controlled by the beds through which they were able to circulate, and in which they deposited their copper.

At other places, probably because of greater fracturing of the rock, the solutions were able to penetrate higher into the series and deposit their copper content in the overlying dolomites, which are evidently very favorable host rocks. It will be seen from an

examination of the map that the principal mines in the Katanga lie in a zone of over-thrust faulting that follows a closely folded anticline of the Série des Mines. In the neighborhood of this thrusting there are a number of transverse faults and at several places these latter have been found to contain sulphide mineralization.

The quartzites and schists of the Muva system have been deformed by later folding that involved the Série des Mines, principally by fracturing. At many places the joints in these rocks contain small veins of quartz and chalcopyrite, and copper-bearing pegmatites. This has been found to be the case at Mufulira and the Roan Antelope mines. These rocks evidently furnished the mineralizing solutions with comparatively free channels from their deep-seated source, and coming in contact with the beds of the Série des Mines, they continued to penetrate upward until they found their path blocked by impervious beds. Where the strata are comparatively little fractured this took place in the lower part of the series, whereas in areas of considerable faulting it took place only when they had penetrated to the horizon of the dolomite and dolomitic shales.

CONCLUSIONS.

1. The principal copper deposits of the Katanga and Rhodesia occur in the lower series of the System of the Katanga, known locally as the Bwana M'Kubwa series, Roan series, Série des Mines, Group schisto-dolomitique-cherteux and Série Metamorphique.

2. For the purpose of simplication, and in view of the fact that these rocks were first studied in the Katanga, where the ore-bearing beds were called the Série des Mines, this name has been adopted and applied by the writer to these rocks over the entire copper belt.

3. The sulphide ore bodies of Rhodesia are found near the base of the Série des Mines. They lie stratigraphically below the

oxidized ores of the Katanga, which are found in the dolomites of the upper Roan group, and to a lesser extent, in the M'Washia.

4. No evidence of unconformity has been found between the Série des Mines and the Kundelungu series, and it is considered that these beds should be grouped together under the name of Katanga System, as proposed by Van Doorninck.

Rhodesian Selection Trust,
N'Dola, Northern Rhodesia.

THE ORIGIN OF THE TALC AND SOAPSTONE DEPOSITS OF VIRGINIA.[1]

J. D. BURFOOT, JR.

THE talc, steatite, and soapstone of Virginia all occur in the area of crystalline rocks, bounded on the southeast by the Coastal Plain and on the northwest by the Valley and Ridge Province. This area is divided into the Piedmont Province on the southeast and the Blue Ridge Province on the northwest. The latter has recently been defined by Jonas[2] as including the entire Catoctin-Blue Ridge Anticlinorium, instead of merely the Blue Ridge Mountains proper. She finds the rocks of the two provinces of sufficiently different character to be classified and described separately. The following table represents her classification.[3] The only one of these rock types which will be referred to in any detail is that with which the talc and soapstone is associated; that is, the metagabbro-metaperidotite group of basic intrusives.

BLUE RIDGE PROVINCE	PIEDMONT PROVINCE
TRIASSIC SEDIMENTARY AND IGNEOUS ROCKS	
ORDOVICIAN SEDIMENTARY ROCKS	
	Everona Limestone, Arvonia Slate, Quantico Slate
CAMBRIAN SEDIMENTARY ROCKS	
Loudoun Formation	
PRECAMBRIAN INTRUSIVE ROCKS	
Felsite dikes	Granite
Hypersthene Granodiorite	Columbia Granite
Albitite	Cartersville Granite

[1] Published by permission of the Virginia Geological Survey. Presented before the Society of Economic Geologists, Charlottesville meeting, April 24, 1930. The author has made a detailed study of the talc and soapstone deposits of Virginia, which will be published as a bulletin of the Virginia Geological Survey.

[2] Jonas, A. I., "Geologic Reconnaissance in the Piedmont of Virginia," *Bull. Geol. Soc. Amer.*, vol. 38, pp. 837–846; Dec., 1927.

[3] Geologic map of Virginia, Virginia Geol. Survey, 1928.

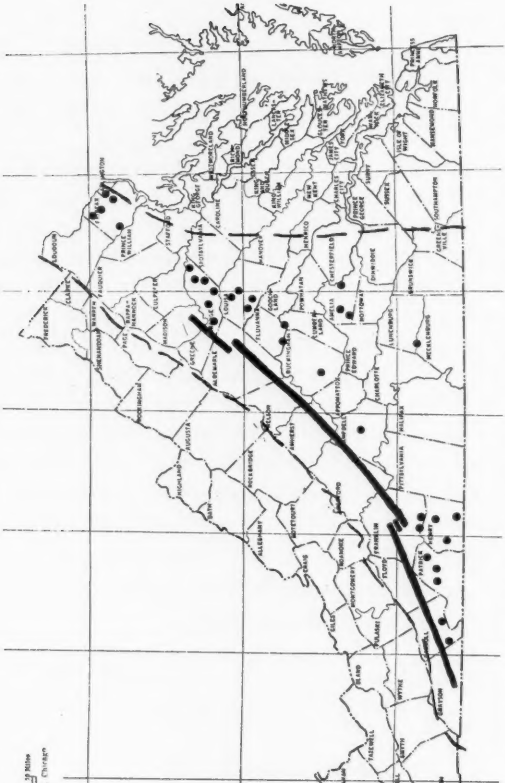

FIG. 1. Outline map of the State of Virginia, showing the distribution of known deposits of talc and soapstone.

Marshall Granite	Red Oak Granite
Lovingston Granite Gneiss	Leatherwood Granite
	Quartz Diorite
Metagabbro-metaperidotite group	Metagabbro-metaperidotite group

PRECAMBRIAN EXTRUSIVE ROCKS

Catoctin Greenstone	Greenstone volcanics
Aporhyolite	Aporhyolite

PRECAMBRIAN METASEDIMENTARY ROCKS

	Glenarm Series:
	Peters Creek Formation
Lynchburg Gneiss	Wissahickon Schist
White Marble	Cockeysville Marble
	Baltimore Gneiss

GEOGRAPHIC DISTRIBUTION.

Talc is a mineral of wide distribution. It occurs in small quantities in many areas of metamorphic rocks and in some areas of igneous ones, but it is rarely found in quantities large enough to work. On the accompanying map (Fig. 1) the broken lines outline the area of crystalline rocks in which the soapstone occurs. The heavy lines on the map represent the so-called Albemarle-Nelson county belt, which extends from Madison county to Grayson county, a distance of more than 200 miles. The most important deposits of this belt are located, as its name implies, in Albermarle and Nelson counties. In fact, this part of the belt is said to produce more soapstone than any other locality in the world. The belt, as a whole, is made up of a series of metamorphosed, ultra-basic, igneous rocks, in which occur unevenly distributed lenses and irregular bodies of soapstone. The scattered circles represent known local deposits, many of which are being or have been worked. The Fairfax county area ranks second in production in the State, with Franklin county, because of the deposit at Henry, third. Other deposits than those shown on this map will undoubtedly be discovered from time to time.

VARIETIES OF TALC FOUND IN VIRGINIA.

Of the many varieties of talc described in the literature, only three have been found in Virginia, viz: (1) Foliated talc (or talc); (2) steatite; (3) soapstone.

Foliated Talc.—This occurs in veins, from a fraction of an inch to six inches in width, which cut the massive varieties of talc and serpentine. Along with the talc, whose foliæ usually stand at right angles to the walls of the veins, may be found carbonate, magnetite, pyrite, and other minerals. The talc may be apple-green, other shades of green, white, or yellowish. These veins are usually present in massive talc deposits, but are of no commercial importance.

Steatite.—Steatite occurs, associated with serpentine, in many sections of Virginia. In its purest form, it is a fine-grained, massive, compact, firm rock of light gray color with a greenish or bluish cast. Under the microscope (Fig. 2), the best grade appears as an interwoven, fine-grained mass of talc flakes of random orientation, with one per cent. or so of chlorite and a few grains of magnetite. With a decrease in the quality of the stone, there is an increase in the percentage of chlorite and of magnetite with carbonate, pyrite, tremolite, serpentine, specularite, titanite, and other minerals appearing in varying quantities. A rough schistosity may also be developed.

Soapstone.—Soapstone is commercially the most important and the most widely distributed variety of talc in the State. In com-

TABLE I.

	1	2	3
Talc	40–85	30	0–5
Chlorite	5–45	20	40–50
Serpentine	0–few	25	0
Amphibole	0–few	15	40–49
Carbonate	5–25	5	0–7
Magnetite	1–5	4	0–2
Pyrite	0–2	1	0–1

1. Soft stone (determined from several specimens).
2. Tough stone (one specimen).
3. Hard stone (several specimens).

position and texture it occupies a position between steatite on one hand and serpentine or metapyroxenite on the other. Megascopically, it is a medium to fine-grained, bluish gray, greenish gray, or grayish green rock showing varying degrees of schistosity and facility for sawing. Table I. shows the percentage in mineral composition of several grades of soapstone as determined from thin sections.

Note that the soft stone contains a large percentage of talc, with considerable chlorite and little or no tremolite or serpentine. On the other hand, the hard stone shows high percentages of amphibole and chlorite with correspondingly low percentages of talc and other minerals; whereas the tough stone carries a large proportion of serpentine along with talc, chlorite, and amphibole. The tough and hard varieties of stone are worked somewhat in the nature of by-products. The composition of the stone selected for use varies considerably from place to place and from time to time in the same locality. The compositions given will, however, apply to the majority of cases.

Figs. 3, 4, and 5 show three photomicrographs of commercial soapstone. This stone in the hand specimen, and for manufacturing purposes, shows a grain, or schistosity. These photomicrographs show, however, that the talc and chlorite have, in general, a random orientation. Fig. 5 shows a rock, which, in the hand specimen, is very schistose. Note that the talc and chlorite have a general random orientation, but that there are zones through the slide in which these minerals have a parallel orientation. The highest percentage of this schistose material found in any one slide, even in the most cleavable stone, was about thirty-five per cent., the remainder of the rock having a random arrangement.

SOAPSTONE AND ASSOCIATED ROCKS.

General Statement.—The rocks included under this heading consist of metagabbros, metapyroxenites, metaperidotites, serpentine, soapstone, and steatite. Perfect gradations exist between the first three of these rocks, and they are undoubtedly differentiation products of the same magma. The last three are special

developments of the first three; therefore, the two divisions will be discussed separately.

The rocks of this group, as a whole, occur rather well distributed over both the Blue Ridge and the Piedmont Provinces as much squeezed dikes, stocks, and plugs with a general northeast-southwest strike. They intrude the pre-Cambrian metasediments of the region as well as the extrusives; but they are thought [4] to be older than the other intrusives, since they are intruded by some of them. They are, therefore, probably middle or early Upper Algonkian in age.

In one locality observed by the author, however, a dike of metapyroxenite seems to be cutting the Loudoun. This would suggest the possibility of their being post-Lower Cambrian in age.

Metagabbro-Metapyroxenite Group.—Megascopically, the metagabbro is a coarse to fine-grained, sometimes porphyritic, holocrystalline, massive or somewhat schistose rock of mottled or speckled appearance, and green or gray color. The color and appearance are caused by a mixture of the light and dark constituents of the rock. The prominent light-colored constituents are quartz and saussuritized feldspar; the dark colored one, amphibole. The saussurite may vary from white to green in color, depending on the relative amounts of feldspar and epidote present. The amphibole may be a black, lustrous hornblende, a green hornblende, or a grayish green or greenish gray actinolite or other amphibole.

The metapyroxenite is merely a feldspar-poor phase of the metagabbro. Like the latter, it is a fine to coarse-grained, holocrystalline, massive or schistose rock. It is dark to light grayish green in color, depending on the amphibole present, the latter giving it a somewhat massively fibrous or splintery texture. The light grayish green variety of this rock seems to predominate and is the one that laymen, and even soapstone quarrymen, often mistake for soapstone.

In thin section, these rocks are seen to contain the following minerals, whose paragenesis, beginning with the oldest, is: Amphibole; albite, albite-oligoclase, epidote, and clinozoisite; ilmenite;

[4] Jonas, Anna I., *op. cit.*

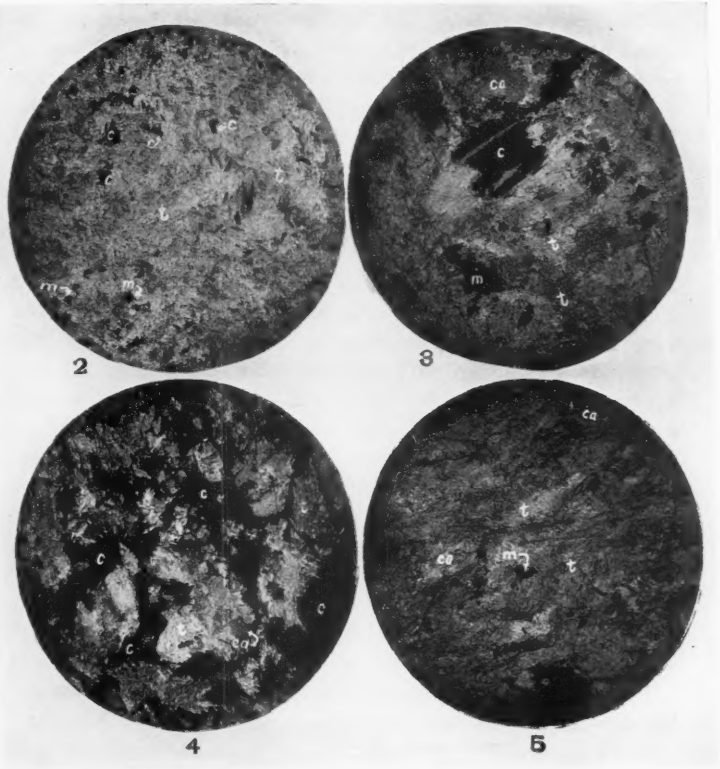

FIG. 2. Photomicrograph of best grade steatite. ×-nicols. ×30.

FIG. 3. Photomicrograph of commercial-grade soft soapstone. Quarries of Virginia Alberene Corporation, Schuyler, Va. ×-nicols. ×30.

FIG. 4. Photomicrograph of commercial-grade soft soapstone. Quarries of Virginia Alberene Corporation, Schuyler, Va. ×-nicols. ×30.

FIG. 5. Photomicrograph of commercial-grade soft schistose soapstone. Quarries of Virginia Alberene Corporation, Schuyler, Va. ×-nicols. ×30.

Talc, *t*; magnetite, *m*; chlorite, *c*; carbonate, *ca*.

titanite; chlorite; talc and magnetite; quartz. All these minerals are not present in every rock, and those that are found vary in amount from place to place even in the same slide. It is not to be understood that this paragenesis is absolute and inflexible, for the stages undoubtedly overlap and may even be reversed in certain instances. Also, one mineral may at times occur in more than one stage. This order is to be looked upon as the usual paragenesis, whose more important steps are inflexible.

The amphibole of these rocks is of two varieties,—a hornblende with a strong green and yellowish pleochroism and extinction angles of from 16° to 20°, and a light green to colorless amphibole with more elongated crystals and having extinction angles up to 23°. The hornblende occurs both as phenocrysts up to nearly one fourth of an inch in diameter and as crystals making up the general mass of the rock, which themselves, in the coarsest types, may reach up to one quarter of an inch across. The amphibole occurs intergrown with the other constituents of the rock, but, in the coarser metapyroxenites, may approach one fourth of an inch in diameter. The crystals usually show the characteristic splintery cleavage, and have a grayish green color in the hand specimen. The amphiboles are the oldest minerals now found in these rocks, and they are replaced by all the succeeding minerals. Their orientation is random, and they are sometimes splintered by crushing.

The albite, albite-oligoclase, epidote, and clinozoisite were all probably formed by the same process; that is, by the breaking down of a plagioclase feldspar. An original labradorite, for instance, probably broke down to form albite or albite-oligoclase on one hand and clinozoisite or epidote on the other.

The plagioclase occurs as well-defined crystals showing the albite twinning. The indices of this feldspar are equal to or below that of Canada balsam with one index sometimes above, and the maximum angles in the zone normal to (010) from fifteen to eighteen degrees. The optical sign where determined is positive. The epidote and clinozoisite are typical in these sections, showing their characteristic high index, rough shagreen surface,

globular or irregular form, the epidote its high interference colors, and the clinozoisite its abnormal Berlin blue interference tints. The characteristic change in iron content from grain to grain or even from place to place in the same grain, as shown by the variation in the strength of the interference colors, is well illustrated. Typical pleochroism is shown by the epidote. The epidote and clinozoisite occur as irregular-shaped grains scattered through the plagioclase, evidently remaining there from the alteration. They also occur as beautiful replacement forms in the amphiboles, evidently having been transported from their places of formation to these points (Fig. 6). This transportation of the epidote seems to indicate that some outside hot waters were active in its formation; for straight dynamic or static metamorphism does not, according to many authors, permit of such transportation. There may be considerable feldspar in the rock with little epidote and clinozoisite, and commonly there is much epidote and clinozoisite present with little or no feldspar. This also indicates transportation.

The ilmenite occurs as non-magnetic, irregular-shaped masses of characteristic color and opaqueness. It replaces the amphibole and may be either original ilmenite in the igneous rock which was collected by hot solutions and re-deposited, or ilmenite brought in by these solutions.

The titanite occurs as characteristic bisphenoids, as irregular grains, and as reaction rims around ilmenite grains (Fig. 7). It displays its usual high index and birefringence and its characteristic brownish pleochroism. It is seen to replace the ilmenite, the epidotes (Fig. 6), and the amphiboles. This sphene was probably formed by the reaction of hot solutions, carrying lime and silica, on the pre-existing ilmenite. The lime and silica may have been derived in part from the breaking down of the original feldspars; for, as shown above, both of the resulting products, the acid plagioclases and the epidotes, were transported in solution.

The chlorite occurs as colorless to light green, and then somewhat pleochroic, fine-grained, felted, irregular to botryoidal-shaped masses. It is seen as beautiful replacement forms with

FIGS. 6–10.

scalloped borders replacing the amphiboles (Fig. 8), in which process it commonly isolates and molds itself around epidote and titanite which have themselves previously replaced the amphiboles.

The little talc which is present in these rocks is seen as characteristic colorless flakes with parallel extinction, high interference colors, and basal cleavage. It has been observed replacing the chlorite and the amphiboles. It occurs in aggregates and in single, scattered flakes. Some of the single flakes are comparatively large and are to be seen with a random orientation replacing amphibole. The size of these flakes, the perfection of their form, and their replacement of the amphibole without apparent regard for the amphibole structure seems to indicate a hot water origin.

Very little magnetite is present, but that noted has the characteristic magnetism and blue gray color in reflected light. It occurs as irregular-shaped masses replacing most of the other minerals. It may have been either brought in by the solutions or liberated to these solutions during the alteration of some preexisting iron-bearing minerals and deposited later.

Quartz is present as clear, interlocking grains filling the cavities between the other minerals and replacing them. It commonly contains a few lines of small, fluidal inclusions and projections and fragments of the other minerals. Some of it may have been brought in by solutions, but some undoubtedly was added to these solutions by the chemical reactions going on in the rock. It is, therefore, thought to be secondary.

FIGS. 6–10.

FIG. 6. Photomicrograph of metagabbro, showing epidote replacing hornblende with titanite replacing both of the former. × 30.

FIG. 7. Photomicrograph showing reaction rims of titanite around ilmenite in a mass of hornblende. Ordinary illumination. × 30.

FIG. 8. Photomicrograph showing chlorite replacing hornblende with a few isolated epidote grains. ×-nicols. × 30.

FIG. 9. Photomicrograph of talcose serpentine rock showing talc replacing serpentine under control of old olivine cracks. Talc also replaces chlorite. ×-nicols. × 30.

FIG. 10. Photomicrograph of serpentine rock showing serpentine retaining old pyroxene forms and hornblende cleavage. ×-nicols. × 30.

Amphibole, *a*; epidote, *e*; carbonate, *ca*; chlorite, *c*; hornblende, *h*; ilmenite, *il*; magnetite, *m*; serpentine, *s*; talc, *t*; titanite, *ti*; tremolite, *tr*.

Origin of the Metagabbro-Metapyroxenite Group.—From the evidence set forth above and from that which is to follow, it seems probable that the original rocks of this group ranged from gabbros to pyroxenites, carrying plagioclase feldspar around labradorite and pyroxene, probably augite. There were peridotites and probably even dunites in this series, but these olivine rocks had, so far as observed, a somewhat different history; so they will be taken up in a different section of this paper.

The gabbros and pyroxenites are thought to have been acted upon by magmatic solutions with the following changes taking place:

1. Pyroxene was changed to green hornblende and to the colorless amphibole.

2. Basic plagioclase feldspar was changed to albite, albite-oligoclase, epidote, and clinozoisite, and some of these, in the process, were taken into solution and transported, part of the epidote and clinozoisite replacing the amphibole on re-deposition.

3. What original ilmenite there was in the rock was taken into solution and possibly added to from the solution source, and then re-deposited as replacements of the amphibole and possibly the epidote.

4. Titanite formed as reaction rims around the ilmenite by the addition of lime and silica and the extraction of iron. It was also taken into solution and re-deposited as replacements of the epidote, and the amphibole.

5. Chlorite replaced the hornblende and colorless amphibole and, in the process, frequently isolated and molded itself around previously formed replacement epidote, clinozoisite, and titanite.

6. Talc in small amounts was formed as replacements of the chlorite and the amphibole.

7. Very little replacement magnetite was deposited.

8. Quartz was deposited, filling in between the other minerals and replacing them.

This series of reactions is thought to have taken place through the agency of hot magmatic solutions, which started at conditions of approximate contact-metamorphic intensity and gradually

cooled, and, while doing so, promoted these reactions and deposited these minerals at the successively cooler temperatures. Evidence will be brought out later which indicates that these solutions were rejuvenated after the chlorite stage and before the deposition of talc.

Geologic Occurrence of the Soapstone Rocks.—The soapstone and steatite occur as lenses or irregular-shaped bodies in or along the edges of the metagabbros and metapyroxenites, and show perfect gradations into these rocks. However, the soapstone in places, and the steatite always grade first into serpentine which in turn grades into the basic meta-igneous rocks. In places the soapstone grades directly into metapyroxenite.

The lenses lie dimensionally parallel to the igneous bodies, which in turn are parallel in dip and strike with the rocks of the region. They vary in dimensions from nothing up to the immense bodies at Schuyler and Alberene, which are approximately 1200 and 2000 feet in length, respectively, up to 300 feet in width, and of unknown depth.

Petrography of the Serpentine, Soapstone, and Steatite.—The higher grade, workable members of this group have already been referred to. In this section I shall take up the group as a whole and discuss the impure, unworkable members along with the high-grade ones.

Megascopically, the serpentine, or amphibole serpentine, is a massive, dense, greenish gray to greenish black rock with occasional flecks of talc and cleavage fragments of carbonate scattered through it. It commonly shows signs of having been crushed, and contains veinlets of talc, carbonate, or chrysotile, either separate or mixed.

Under the microscope, the serpentine-soapstone-steatite rocks are seen to contain the following minerals, whose paragenesis, beginning with the oldest, is: Amphibole; biotite; chlorite; serpentine and magnetite; tremolite; talc, magnetite, carbonate, chrysotile and pyrite; tremolite; specularite.

This is not to be taken as the absolute order of formation of these minerals, for these stages may overlap one another con-

siderably or even, in rare cases, be reversed. Furthermore, most specimens will not show all these stages, and any assortment of these minerals varies considerably in percentages from place to place. This order is to be taken as the general paragenesis which will hold in the great majority of cases.

The amphibole occurring in these rocks is a colorless to grayish green or greenish gray, splintery mineral with the usual amphibole cleavage, cross fractures, index, birefringence, and an extinction angle of 23°. This mineral is thought to be the oldest mineral occurring in these rocks and to be formed from a pre-existing pyroxene.

Biotite is not particularly common in these rocks. It occurs as strong yellowish brown cleavage masses with decided pleochroism and the usual birefringence, index, and bird's-eye-maple structure, filling interstices between amphibole and replacing it. It has all the aspects of a mineral deposited by hot water. The replacement material occurs as smears and colorations throughout the amphibole. It has none of the aspects of residual biotite from an original igneous rock.

The chlorite occurs in these rocks in two forms; viz.: (*a*) in comparatively large sized, colorless to faint green, usually crinkled pieces with low index, grayish green interference colors, and basal cleavage (Fig. 3); and (*b*) as fine-grained, felted masses of irregular outline with about the same optical properties as the larger pieces, except that the interference colors range from black to grayish green (Figs. 4 and 8). The chlorite in large pieces is clearly replaced by serpentine, magnetite, talc, carbonate, and pyrite. It is thought to be the oldest mineral in the metadunite (or metaperidotite) in which it occurs, and judging from its occurrence, to be derived from original biotite in this rock. The fine-grained chlorite occurs in the metaperidotites and metapyroxenites as interstitial material between serpentine aggregates which will be described in the following paragraph (Fig. 10). It is seen replacing the amphibole and to be replaced by serpentine and talc. It is very close in time to the following serpentine stage, and undoubtedly overlaps it considerably. In this respect

it is different from the flake chlorite. It is probably formed from the amphibole, especially from the more aluminous varieties.

Serpentine is seen in these rocks as tiny stringers and flaky, felted, colorless to faint green aggregates of rounded, irregular, or polygonal form, low index, and distinct grayish to whitish blue interference colors.

In the serpentine rocks derived from metadunites, the serpentine occurs as rounded to polygonal-shaped aggregates with the flakes arranged in a roughly radial fashion (Fig. 9). The old olivine cracks are filled with separated magnetite, fine-grained serpentine, and talc. Extending from either side of these cracks, flanking them, and arranged peripherally around the serpentine aggregates and sending tongues radially into them and replacing them are rings of talc. This is an excellent example of replacement with the replacing mineral showing definite relation to the feeding cracks. In these rocks, the serpentine is seen to replace the chlorite and to be replaced by talc and some of the other minerals of the talc stage. As indicated, it is thought to be derived from the serpentinization of olivine.

In the serpentine rocks derived from metapyroxenites, the serpentine occurs as rounded to polygonal-shaped aggregates with the flakes and stringers crossing one another at angles varying from the amphibole cleavage angles to ninety degrees or zero (Fig. 10). The external shapes of these aggregates closely resemble old pyroxene forms. In some cases, the eight-sided pyroxene crystal form is preserved. Through these forms extend the stringers and flakes of serpentine, arranged symmetrically in reference to the external shape. Peripherally around them are needles of tremolite replacing the serpentine, with later talc replacing both the tremolite and serpentine. Carbonates, magnetite, and pyrite also replace the serpentine and tremolite. The serpentine itself replaces the chlorite and amphibole. These serpentine forms are thought to be old pyroxene shapes with the uralite cleavage preserved by the serpentine structure.

The tremolite described above occurs in small, colorless needles or prisms of typical index, birefringence, and extinction angle.

The talc of the serpentine rocks has been described above as occurring in individual flakes and as series of flakes forming rings around the periphery of the serpentine masses. In the rocks free from serpentine, those talc-bearing rocks in which the serpentine stage is missing, the talc occurs as small, individual flakes and as fine-grained, felted areas between amphibole crystals and replacing them. In all cases, the talc is a colorless mineral with good basal cleavage, low index, high birefringence, parallel extinction, and bird's-eye-maple structure. It replaces the tremolite, the serpentine, the chlorite, and the amphibole. The relatively talc-poor rocks described here gradually increase in their proportion of talc by replacement until high-grade, workable soapstone and steatite are reached.

Accompanying or closely following the talc are magnetite, pyrite, carbonate, and chrysotile. The magnetite occurs as grains and irregular-shaped masses both released during the process of talc formation and collected by the talc-forming solutions from the disseminated material released during serpentine formation, and re-deposited. The carbonate has the same occurrence and probably the same origin. These minerals, along with chrysotile, are also deposited in veinlets cutting the main mass of rock.

A third generation of amphibole in the form of secondary growth tremolite occurs in some of the amphibole-talc rocks as long, slender, needle-like spines growing on the ends of tremolite crystals parallel to the "C" axis. The primary growth amphibole is replaced by the talc, showing corroded sides and ends, but the second-growth tremolite occurs as fine, acicular, clear needles replacing the talc. This later tremolite seems to be out of place; but, since it has been observed from only one locality, it probably was formed by the breaking away of some barrier or obstruction to the feeding solutions and thus allowing a rejuvenation of conditions.

Specularite occurs in some of these rocks as grains, irregular-shaped bodies, and stringers between leaves of chlorite and talc. In transmitted light, it is blood red on the thin edges; in reflected light, it is steel gray to black. It is probably the youngest mineral

of the series, for it is seen replacing talc, serpentine, chlorite, biotite, and amphibole.

Origin of the Serpentine, Soapstone, and Steatite.—It is probable that the original rocks of this group were pyroxenites, peridotites, and dunites, representing separate bodies or segregations in larger bodies. These rocks were acted upon by hot waters with the following changes taking place:

1. The pyroxene was uralitized to amphibole, in some cases preserving the external form of the pyroxene but taking on the internal structure of the amphibole.

2. Biotite was introduced in a few localities as replacements of the amphibole and as fillings of any existing cavities. This stage probably overlapped the uralite stage to some extent.

3. Chlorite replaced the biotite of the dunites. In the peridotites and pyroxenites, it replaced the biotite and some of the amphibole. It possibly preferred the interstitial, aluminous amphibole to the then pyroxene-shaped bodies.

4. Olivine was altered to serpentine with the separation of magnetite along the cracks of the olivine. The uralite bodies were also serpentinized with the cleavage of the amphibole and the external form of the pyroxene preserved. The interstitial chlorite was affected but slightly, probably because of the greater similarity in composition and conditions of formation of serpentine and chlorite. Some magnetite was undoubtedly released during this latter process, and carbonate was probably released during the serpentinization of both the olivine and the uralite.

5. This stage represents the rejuvenation of the solutions,—the water became hotter and the conditions in general more intense. With this change, tremolite was developed around the edges of the now serpentinized uralite bodies, replacing the serpentine and to some extent the chlorite.

6. With the cooling of the solutions, talc, magnetite, carbonate, and pyrite were developed. In the rocks which previously bore olivine, the solutions worked in along the old olivine cracks and spread out from them laterally, replacing the serpentine. In the old pyroxene-bearing rocks, talc replaced tremolite, serpentine,

chlorite, and uralite in the form of flakes. Along with this development of talc, magnetite, carbonate, and pyrite were formed. The magnetite and carbonate were probably released, to some extent, by the talc-forming reactions, but they were also collected from that already formed, and re-deposited. Pyrite was probably introduced from the outside. The rock seems to have been fractured slightly during this stage, and talc, chrysotile, and the other minerals were deposited in the cracks in the form of veinlets, the chrysotile fibers standing at right angles to the walls of the fractures.

7. In one locality is a secondary growth of tremolite with slightly later specularite. It is thought that here the feeding solutions died out or were choked off. Then the source was rejuvenated or some barrier in the path of the solutions was removed, the solutions were again given free access to the rock, and these minerals were formed.

It is not to be understood that all these steps are shown in any one rock or in any one locality; in fact, no locality shows all of them, and some show only a few of them.

Definite evidence as to whether or not talc in some cases replaces the country schist is lacking. Several occurrences were seen in which talc apparently grades into the schist in a manner similar to replacement, but the outcrops are so badly weathered that accurate megascopic or microscopic evidence was unobtainable.

The stages that have brought these rocks to their present state seem to correlate quite well with the stages of the metagabbro-metapyroxenite development. As has been indicated, there were either two invasions of solutions or a decided rejuvenation of the already invading solutions. The first invasion, which was very widespread and affected both divisions of the rocks, started with the formation of amphibole and deposited, during cooling, the succession of minerals through chlorite and serpentine. The second, which was quite local and affected only the talc-bearing rocks, began with the formation of tremolite and continued as it cooled through the talc or specularite stages, depending on the locality.

Hot magmatic[5] solutions are thought to be responsible for these changes for the following reasons:

1. The minerals present and their occurrence are highly indicative of hydrothermal solutions.

2. The order in which these minerals were deposited suggests strongly that cooling solutions were responsible.

3. In rocks formed by dynamic metamorphism (or under conditions of movement), there would be expected no such random orientation of the mineral components as is found in these rocks.

4. According to many authors, dynamic or static metamorphism permits of no such transportation of the mineral constituents from place to place as is observed in these rocks.

5. It is doubtful if meteoric water could reach to the depth necessary for the formation of these minerals in sufficient quantities for such transportation as has occurred.

6. It is to be expected, when such an insoluble assemblage of minerals as this is transported, that the intense conditions of temperature, pressure, and character of the solutions found in waters from a magma would be necessary.

7. The presence of talc of random orientation in comparatively large, yet well-developed cleavage flakes replacing the amphibole suggests hot water as its origin.

8. The presence of the replacement talc, showing dependence on cracks, suggests fluidal solutions as being the active agent.

9. The rejuvenation of conditions, as evidenced by the recurrence of high-temperature minerals, without crushing of the previously-formed minerals and with many of the previously-formed minerals remaining unchanged, points strongly to a hot water origin.

10. Magmatic waters best explain the geologic occurrence and relationships of these rocks.

These hot waters must have carried carbon dioxide and silica throughout the greater part of their active period. During the

[5] This theory is contrary to the one suggested by C. W. Ryan, who holds that the schists and intrusives were changed to soapstone through the action of mineralizers derived from the country schists. See *Amer. Inst. Min. and Met. Eng.*, Tech. Pub. 160, 1929.

formation of titanite, the presence of lime in addition to silica was necessary. This may have been derived from the breaking down of the calcic plagioclases to form acid plagioclase and epidote or clinozoisite. When chlorite and serpentine were formed, the solutions became lower in silica and lime, and richer in magnesia and carbon dioxide. In the following stage of talc formation, lime was still low except in the localities where tremolite was formed, and silica and carbon dioxide were high. In the last stage of specularite formation, oxygen became higher locally.

In the reactions that went on in these rocks, carbon dioxide was necessary to take care of any extra base, especially bases which were not needed in the formation of the mineral being actively precipitated. In this role it had, in part, the same function as silica would have, for they both tend to increase the silica percentage of the minerals formed, the carbon dioxide having the additional function of removing bases not needed. The presence of abundant carbonates and some quartz throughout these rocks bears testimony to the presence of these two substances. It is thought that oxygen was plentiful in the final stage, because specularite was formed in preference to magnetite.

In addition to the composition of the active solutions, temperature and pressure are necessary to provide the environment suitable for the development of any mineral. It is thought that the silica and water percentage of a mineral, as well as its breaking down or building up, can be changed by the variation of these two factors alone.

There are many igneous rocks in this region of Upper Algonkian age, whose magmas may have been the source of the solutions that altered these basic rocks. In fact, it is probable that more than one magma furnished these solutions. This would be a factor in accounting for the variation in composition of the altered rocks from place to place. These Upper Algonkian intrusives vary in composition from granites through quartz monzonites to granodiorites and quartz diorites. If these rocks are the sources of the active hydrothermal solutions, then the alteration of the gabbros and pyroxenites took place during Upper Algonkian times.

Two other possible sources of the solutions are the magma that gave rise to the felsite dikes, and the mother magma of the basic rocks themselves. If the soapstone rocks are post-Lower Cambrian in age, one of these latter two magmas must have been the source.

The lens-shaped occurrence of soapstone is undoubtedly connected with the lens-shaped occurrence of all the igneous rocks of the region. These rocks have either been intruded along the schistosity of the country rocks, or they have been squeezed into their lens-shaped forms. The talc occurs as replacements either of whole bodies or of segregations in larger bodies. These segregations have passed through the same conditions as the larger bodies of which they are a part; therefore, they, too, tend to have lens shapes. Futhermore, if there are any fracture or cleavage lines developed in the rocks, they will, in the main, tend to parallel the schistosity of the region and the solutions will work along and spread out from them, tending to develop elongated or lens-shaped bodies.

The presence or absence of talc, soapstone, or steatite in this region is thought to depend, in part at least, upon:

1. The occurrence of the correct segregation product,—pyroxenites, peridotites, or dunites.

2. Presence of feeding channels leading to these rocks.

3. The invasion of the correct type of solutions; that is, solutions of the correct chemical character with the requisite temperature and pressure.

This study of the origin of talc suggests the following points relative to its conditions of formation:

1. The condition of differential stress is not necessary for the formation of talc. None of the talc studied shows over thirty-five per cent. of the mineral having parallel arrangement; whereas, the great majority of the sections studied show almost all the talc flakes to have random arrangement.

2. The mineral association and paragenesis seem to indicate that talc is formed under deep or intermediate vein zone conditions. These conditions of talc formation might be expressed in

the following manner: $X \times Y \times Z = K$, in which, $X =$ temperature, $Y =$ pressure, $Z =$ composition and character of the solution, and $K =$ conditions of formation of talc. This means that the temperature and the pressure might vary considerably with a corresponding change in the composition and concentration of the substances in solution and still retain the correct conditions for talc formation. Also, K is not a true constant, since it may vary within certain limits.

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THE PLOTTING AND MEASUREMENT OF EXAGGERATED CROSS-SECTIONS.

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In connection with plotting and measuring sedimentary strata in cross-sections having exaggerated vertical scales certain geometrical problems arise for which the writer does not recall having seen any published solutions or modes of procedure. It is true, of course, that wherever possible the same scales should be used for both vertical and horizontal distances, but there are some instances, particularly in connection with the large-scale portrayal of structures at dam sites and in connection with other engineering projects, where it is impracticable to make the vertical scale as small as the horizontal.

Wherever the vertical scale is exaggerated, it is evident that all angles of dip are distorted to appear steeper than their true values and must be plotted by the use of percentage grades or tangents measured on the two scales, or by the use of an

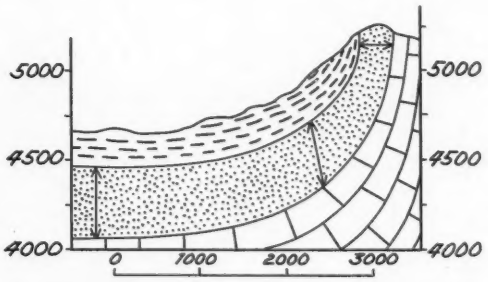

FIG. 1.

elliptical protractor. It is probably not so generally appreciated that thicknesses must be shown in accordance with the two different scales where the beds are vertical or hori-

zontal and with intermediate values for intermediate attitudes. Moreover, in the measurement of thickness of oblique strata an appropriate intermediate scale must be used and the distance determined along a line which is not normal to the bedding. (See Fig. 1.) The true position of this line is found

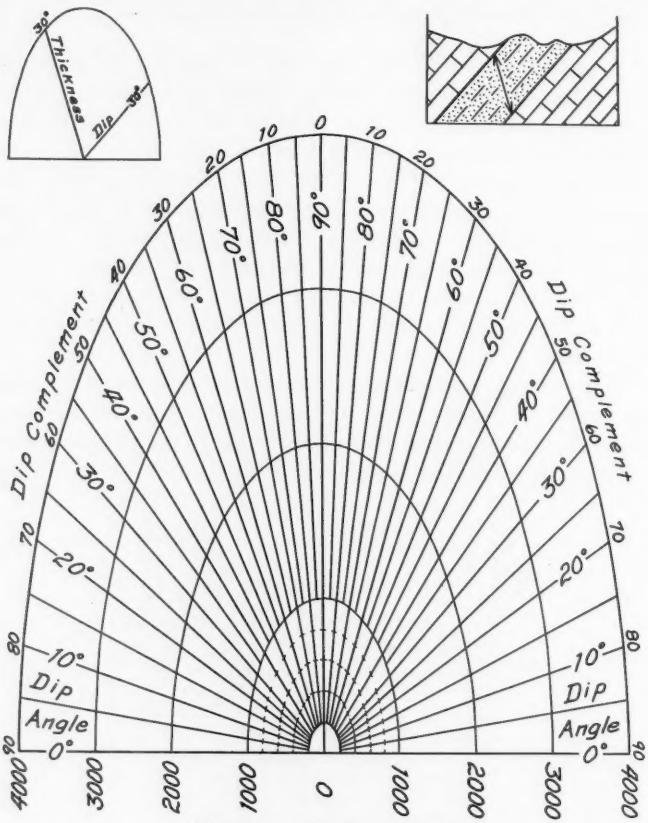

FIG. 2.

by reading the position of the dip angle complementary to the true dip off the opposite side of the appropriate elliptical protractor. Such a protractor plotted for a vertical exaggeration of 2: 1 and provided with graded thickness scales is shown in Fig. 2.

It is hardly necessary to demonstrate that exaggeration of the vertical scale results in the transformation of figures that are circles in true section into ellipses which have vertical major axes in the plotted section. It will be apparent to all who have considered the strain ellipsoid as used in structural problems that in the distortion of angles of dip the angles nearer ninety degrees become more closely spaced and that angles which are complementary to each other in the ground are no longer at right angles to each other but are stretched to show somewhat acute angles in the section.

For any given ratio of exaggeration all the problems involved may be solved by the construction of an elliptical protractor of the type shown. The simplest method of doing this is indicated in Fig. 3. A small circle is drawn with a

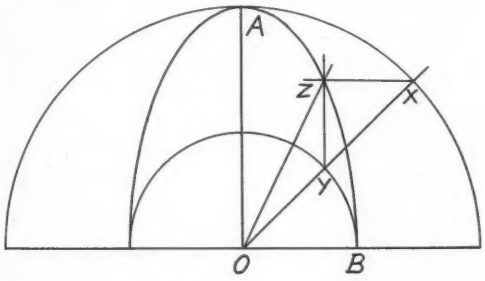

FIG. 3.

radius of any convenient round number of units in the proposed horizontal scale. With the same center a larger circle is drawn with a radius of the same number of units in the exaggerated vertical scale. To determine the position of any distorted angle as well as the corresponding intermediate elliptical radius which forms the scale, the true angle *BOX* is

laid out with a common protractor. Then draw a horizontal line through the point *X* and a vertical line through the point *Y*, calling the intersection *Z*. *OZ* is the position in the exaggerated section of the line *OX* of the natural section and *Z* is a point on the ellipse which has a major radius *OA* and a minor radius *OB*, and which, in the section, is the locus of all points which, in the ground, are at the distance *OB* from the center *O*. By plotting a sufficient number of such angles on one side, the corresponding one-fourth of the required boundary ellipse can be constructed. Intermediate ellipses for scale purposes can most readily be constructed by subdividing radii into the required number of parts with a proportional divider or similar device. The half ellipse can be completed by reversing the quarter already constructed and copying it. In this way a chart of the sort shown in Fig. 2 is readily developed.

If there be those skeptical of the propriety of measuring thicknesses along an apparently oblique line, Fig. 4 will show

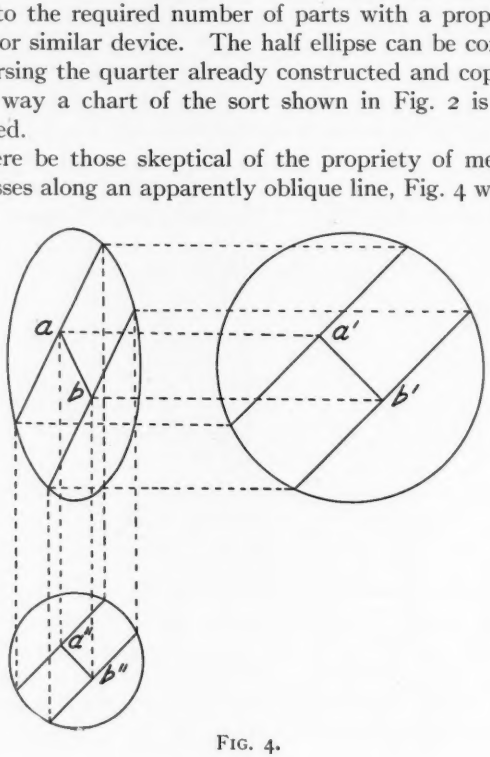

FIG. 4.

that this is a necessary consequence of the exaggeration. Here two circles with similar oblique stratum bands but of different scales have been used in the construction of the corresponding ellipse having a vertical axis equal to the radius of the larger circle and a horizontal axis equal to the radius of the smaller circle. The reader will see that the normal line $a'b'$ and $a''b''$ in the circles has become the oblique line ab in the ellipse, and that its length is one third of the appropriate diameter of the ellipse, as was the case in the undistorted circles.

Once constructed, the elliptical protractor is used as indicated in Fig. 2. Ordinary dip angles as determined in the field are read on the protractor and the indicated lines used in plotting dips. The position of the line along which thickness may be plotted, or measured, as the case may be, is determined by reading the numerical value of the dip angle in the dip complement scale on the opposite side of the protractor from that used for the dip. This is equivalent to using the angle complementary to the dip angle and reading it on the opposite dip scale. Thicknesses are measured by reference to the radius indicated, using the subdivided end near the center for estimating fractional parts. The use of such a protractor or the essential construction for a given case will obviate many of the discrepancies met with if sections are plotted at unequal scales without close regard for the consequences of distortion.

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CLAYS OF THE JACKSON PURCHASE REGION, KENTUCKY.[1]

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INTRODUCTION.

THE Jackson Purchase region of Kentucky lies between the Tennessee and Mississippi rivers, and embraces eight countries. The geology of this region ranges from the limestone and chert of Mississippian (St. Louis formation) to the Recent surficial deposits. The geologic column for the region is as follows:

CENOZOIC:
- Quaternary:
  - Recent surficial deposits,
  - Pleistocene loess and loam.
- Plio-Pleistocene gravel and sand ("Lafayette").
- Tertiary:
  - Jackson clay and sand (Upper Eocene),
  - Grenada clay and sand (Upper Wilcox),
  - Holly Spring clay and sand (Middle Wilcox) (Lower Eocene),
  - Porters Creek clay (Lower Eocene).

MESOZOIC:
- Upper Cretaceous:
  - Ripley sand and clay,
  - Eutaw sand and clay,
  - Tuscaloosa gravel.

PALEOZOIC:
- Mississippian:
  - St. Louis formation.

The clays of the region are quite similar in their properties, mode of occurrence, and age relationships to those southward in Tennessee, and other regions of the great embayment area.

It is not known when clay was first used in this region. How-

[1] Read before the Society of Economic Geologists, Charlottesville meeting, April 26, 1930. By permission of W. R. Jillson, State Geologist of Kentucky.

ever, ball clay was discovered in western Tennessee in the year 1887. There are no available records of shipments of ball clay from Kentucky until 1900, though it was used locally in the manufacture of pottery nearly half a century ago. The clay is shipped generally under three classes, namely ball, sagger, and wad, with several varieties of the first. In 1928 Kentucky led in the production of ball clay, and practically all of it came from the Jackson Purchase region.

The commercial clays range in age from the Ripley through the Wilcox to the Recent. By far the most important clays come from beds of Wilcox age, and from the formation commonly known as the Holly Springs.

DESCRIPTION OF THE CLAYS.

Ripley Clay.—The clay of Ripley age occurs in Calloway, Marshall, and McCracken counties. It has been used in Calloway County for about 50 years in the manufacture of pottery. The only pits operating at present are located in Marshall County. The clay occurs in lenses in the sand, or interbedded in layers along with the sand. The lenses are known to occur as thick as 8 feet, but the layers do not exceed a foot. To the south, the clay is a lighter color, while to the north it is dark, due to organic matter. The lighter-colored clays tend to run higher in grit and sand, and the darker ones carry appreciable amounts of marcasite as concretions. The Ripley clay is sold as wad and sagger clays. The Ripley nowhere in Kentucky, so far as known, shows any marine fossils as in Tennessee, but yields a few fossil plants. It is probably of estuarine origin.

Porters Creek Clay.—The Porters Creek clay occurs in a narrow but broken belt over Calloway, Marshall, and McCracken, and a small area in Graves County. It has never been used, although it aroused interest this past summer as a possible substitute for Fullers' earth. Tests on this clay in Henry County, Tennessee, show it to have too high a shrinkage for bricks. It is a smooth clay, rather uniform in its properties, and free from sand, except in a few layers now and then, and a few sand dikes.

It is a light to medium gray color when dry, has a fairly good plasticity, and little impurities. In thickness it varies from a few feet up to 40 feet. It is of marine origin as indicated by its fossils, and is the only Tertiary clay of the entire region of marine origin.

Holly Springs Clay.—This is the most important of all the west Kentucky clays. It occurs in Graves and Ballard counties in commercial quantities, and in several of the other counties. One of the largest clay pits in the embayment region is being operated near Mayfield, Graves County, known as Old Pit No. 4. The clay shipped from the Holly Springs horizon is classed as ball, sagger, and wad. The clay is blended to meet various requirements of the ceramic industry.

The clay varies from a white through the various shades of gray to black. Organic matter is the chief coloring agent. The darker varieties grade into an impure lignite. Iron oxides are low generally, though thin layers may occur at intervals in some of the pits. All the ball, sagger, and wad clay from this region come from five pits in Graves, and one pit in Ballard County. The sections in these pits have a number of similarities, but only two of the pits furnish fossil flora by which their age is determined. The thickness of the Holly Springs formation attains as much as 50 feet in actual exposures, but the workable lenses of clay do not exceed 25 feet, and are commonly much less. The origin of the Holly Springs clay is certainly not marine; it is most likely due to the filling in of basins left by the withdrawing sea, similar in general to the many lakes along the lower course of the Mississippi River. Neither the clay or sand contain any fossil fauna, except a few beetle elytra and dragon-fly wings.

Some of the recent analyses of this clay have been furnished by the Mandle-Porter Clay Company, and are given in Table I.

Grenada Clay.—Clays of Grenada age occur in the southwestern portion of Graves County, and extend over into Hickman and Fulton counties. These clays are quite sandy, and so far have not been used. Ries lists analyses for these clays.[2] Nearly all

[2] Ries, Heinrich, U. S. Geol. Surv. Prof. Paper 11.

TABLE I.

	1	2	3	4	5	6	7
SiO_2	51.90%	47.00%	46.55%	51.50%	53.78%	56.95%	63.72%
Al_2O_3	32.72	30.18	32.45	30.84	28.74	30.41	26.40
FeO	1.02	1.33	.55	.26	1.01	.89	.53
CaO	.31	.67	.67	.51	1.42	.41	.38
MgO	.27	.37	.37	.23	.12	.16	.20
Na_2O	.76	.77	.77	.45	.49	.49	.49
K_2O	.78	.32	.32	1.26	1.18	.75	.75
Ign. loss	12.50	18.73	18.78	14.90	12.98	10.15	8.29
Total	100.24%	99.37%	100.46%	99.95%	99.72%	100.15%	100.76%

of the clay observed is a light gray to white, and very little of it is lignitic. It contains small crystals of gypsum, though not to as great an extent as in Tennessee. It is not over 25 feet in thickness. It carries very few fossils, and it is identified by its extension from Tennessee and on a lithologic basis.

Jackson Clay.—Clay of Jackson age occurs in Hickman and Fulton counties along the Mississippi River bluffs beneath the Plio-Pleistocene gravel and sand and the loess. The clay is interbedded with the sand, and contains considerable amounts of sand. To the south of Hickman, the clay is indurated, and of a light bluish gray color. It has far less plasticity than either of the Wilcox clays, and so far it has not been used to any extent. The beds attain as much as 40 feet in thickness. It origin is, perhaps, similar to that of the Wilcox clays, as suggested by the fossil flora. At times this clay is quite lignitic in Tennessee but to a far less extent in Kentucky.

Pleistocene Læss and Recent Clays.—The læss deposits occur along the Missisippi River bluffs in all the four counties bordering on this river. The best exposures are in the vicinity of Hickman and Columbus. The læss is of a uniform texture, but varies somewhat in its plasticity. It may become gritty at times. Calcareous concretions are common in all of it, especially near the base, and here gravels also occur. The color is a dark gray, and weathered portions of it assume a yellowish tone. It has been used for brick and tile. The thickness reaches as much as forty feet. Its origin is unsettled, some claiming an æolian, others an aqueous origin.

The Recent surficial clays are widespread over the entire region, and are used only for the manufacture of brick. Some of them apparently are weathered from the underlying materials, others are of fluviatile origin. All of them are red to brown in color, and burn to the usual red brick color.

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HYDROTHERMAL OXIDATION AND LEACHING EXPERIMENTS; THEIR BEARING ON THE ORIGIN OF LAKE SUPERIOR HEMATITE–LIMONITE ORES: PART II.*

JOHN W. GRUNER.

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THE INDIVIDUAL DISTRICTS.

The Gogebic District.[30]—The Ironwood formation of this district, though not much folded, dips at angles of 50 to 70 degrees to the north. It lies on the Palms quartzite conformably and is overlain by the thick Tyler slates. These three formations are upper Huronian in age. Ferruginous chert and sideritic slaty beds make up the bulk of the iron formation. The ores are chiefly soft and porous hematite with minor amounts of limonite.

Hotchkiss[31] describes the shape of the ore bodies in the fol-

* Continued from p. 719.

[30] Irving, R. D., and Van Hise, C. R., "The Penokee Iron-bearing Series of Michigan and Wisconsin," U. S. Geol. Survey Mon. 19, 1892.

Hotchkiss, W. O., "Geology of the Gogebic Range and its Relation to Recent Mining Developments," *Eng. and Min. Jour.*, vol. 108, pp. 443, 501, 537, 577, 1919.

[31] *Op. cit.*, pp. 577 and 578.

lowing manner: "In many cases they taper off at each end and are largest in the middle. Some of them extend from the surface to the greatest depths that mining has penetrated them.[32] Others are entirely underground and do not appear on the surface. . . . In fact it is the general history of the range that the deeper the mining has gone the larger have been the ore bodies. They are nearly always associated with basic dikes of Keweenawan age. Hotchkiss[33] writes: "It may seem at first thought to be unwise expenditure to 'explore for dikes,' but when it is recalled that the ore is found lying on these dikes and at six or more different horizons in the iron formation, the importance of knowing just where the dikes lie is obvious."

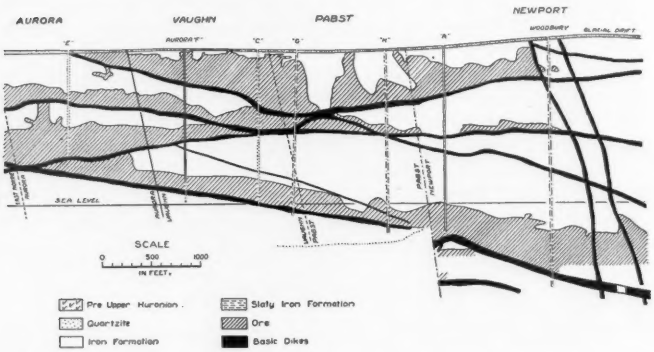

FIG. 6. Longitudinal section of part of the iron formation of the Gogebic district. Section is parallel to dip. Dikes projected on the footwall quartzite. (After the Oliver Iron Mining Company.)

The ore bodies are frequently stacked one above the other, as shown in Figs. 6 and 7, lying on dikes which cut the iron formation at different elevations. According to Van Hise, Leith and Hotchkiss the ore bodies are quite independent of the pitching troughs.

Faults are common in the productive portion of the range.

[32] The deepest shaft at the time of writing reaches a depth of 3277 feet. Ore is known to extend to 4000 feet depth on this range. J. W. G.

[33] *Op. cit.*, p. 581.

The largest one, called the bedding fault, is known to exist for many miles in and parallel to the bedding of the iron formation. Many transverse faults seem to have also been of great influence in the making of the ore bodies. The most favorable conditions for the formation of ore seem to have been at the intersections of dikes with basal quartzite, with slaty layers or with other dikes, though occassionally some ore is found underneath a dike. Fingering of ore bodies upward from the dikes along beds which were exceptionally rich in iron minerals before leaching is common. At the contact with some dikes, exceptionally hard steel blue hematite is found, according to Van Hise and Leith.[34].

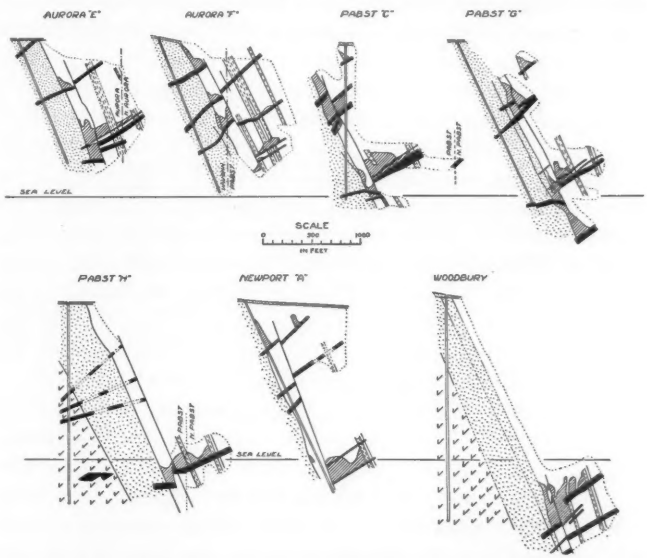

FIG. 7. Cross sections of the iron formation shown in Fig. 6. (After the Oliver Iron Mining Company.)

While most dikes pitch toward the east a number of them pitch westward, a condition which should have greatly complicated progress for descending waters. The intake on the old erosion

[34] Mon. 52, p. 240.

surface would have been relatively very small for each deposit. How such waters after a descent of perhaps a mile or more (assuming some erosion) to a depth of 2000 to 3000 feet below sea level, could still be leaching and oxidizing, and then find their way back to the surface, is a problem which even the staunchest supporter of the weathering hypothesis has not solved.

According to the hydrothermal hypothesis these perplexing questions seem to be answerable by the following course of events: The iron formation was highly fractured due to igneous activity. Dikes were intruded in the most shattered portions. The iron formation was heated, especially where steam and other gases accompanied the intrusions. Some of this steam may have been generated from water that happened to be in the formations. Only where the hydrogen formed in the oxidation of minerals could escape rapidly, oxidation of siderite, silicates and magnetite proceeded and became almost complete. That was clearly above the dikes, where the heat was most intense. The volume changes in the iron minerals due to oxidation helped to disintegrate the cherts. Therefore the richer a layer was in iron minerals the more readily it could have been leached of silica by the waters which rose probably chiefly through the faults and partly along the dikes. The close relation of outcropping ore bodies to the present surface is somewhat doubtful when it is considered that much erosion has taken place. This does not exclude, however, oxidation as far up as the surface at the time of ore formation.

The lack of ore bodies in the western part of the Gogebic range is probably not due so much to recrystallization of the iron formation to a slightly coarser grain and the formation of amphiboles, as to lack of extensive faulting and hydrothermal activity. The gabbro which overlies the iron formation in this part of the district at some distance to the north may be the cause of this lack of ore concentration.

The Marquette District.[35]—The middle Huronian iron formation rests conformably upon slate and quartzite. It is overlain unconformably by upper Huronian Goodrich quartzite. These

[35] Van Hise, C. R., and Bayley, W. S., "The Marquette Iron-bearing District of Michigan," U. S. Geol. Surv. Mon. 28, 1897.

formations are highly folded and intruded by many and sometimes large masses of basic composition. The iron formation consists of jaspers, ferruginous cherts, and sideritic slates. The ores are chiefly porous soft hematites (including martite). Considerable masses of hard ore consisting of specular hematite and smaller amounts of magnetite and martite also exist. In some places this hematite is micaceous in texture.

Van Hise, Bayley and Leith [36] divide the ore deposits according to stratigraphic position into three classes: (1) ore deposits at the bottom of the iron formation; (2) ore deposits well within the iron-bearing formation; (3) ore deposits in the top layers of the iron formation and the bottom layers of the Goodrich quartzite. Some of these bodies are almost wholly in the Goodrich quartzite.

The complexity of the ore bodies is shown best by quoting from these authors: [37]

> In any of these classes the deposits may be cut into a number of bodies by a combination of greenstone dikes and masses. A deposit which in one part of the mine is continuous may in another part of the mine be cut into two deposits by a gradual projecting mass of greenstone which passes into a dike, and each of these may be again dissevered, so that the deposit may be cut up into a number of ore bodies separated by soapstone and paint rock. . . . The ore bodies grade above and at the sides into the jasper in a variable manner.

There may also be mentioned the so-called "hanging" ore bodies, which are surrounded by unleached iron formation on all sides.

Here, as on the Vermilion range, there exists a transition from hard to soft porous ores in some deposits. Van Hise and Leith [38] refer to it in the following way: "Also the upper part of an ore deposit may be at the topmost horizon of the iron-bearing formation and be a specular ore, whereas the lower part may lie wholly within the iron-bearing formation and may be a soft ore." This transition may be abrupt. It is thought that these hard ores

[36] Mon. 52, p. 271.
[37] *Idem*, p. 272.
[38] *Idem*, p. 271.

originated by weathering at an earlier period and were metamorphosed at the time of folding of the formation. That may be the case, of course, but would it not be the most unusual coincidence to have the hard ore deposits extended downward by weathering after this intervening period of anamorphism? Why should the ore have been metamorphosed during this anamorphism while the adjoining and underlying iron formation was not changed to the "usual" amphibole-magnetite-quartz rocks? The formation is supposed to have remained in the form of ferruginous cherts and carbonates. Otherwise it could not have been weathered to soft ore during the second period of ore concentration.

That Van Hise and Leith [39] also consider a quite different possibility of hard ore formation is shown in the following paragraph: "To some slight extent also similar hard ores may have developed directly from the original cherty iron carbonates by deep burial or igneous contact action, but it is shown elswhere that such action usually results in lean silicated iron-bearing rock rather than rich ore bodies."

It is an important question, whether the presence of hard ores and micaceous hematite definitely establishes a period of ore concentration previous to upper Huronian time. It is conceivable that micaceous hematite could have been produced from originally lamellar specular hematite of the iron formation, by the leaching of the silica between the hematite and the pressures which attended the large intrusions that introduced leaching solutions. This opinion of the present writer seems to be supported by the following observation of Van Hise and Bayley: [40]

> A close examination of the slate ores (micaceous ore.—J. W. G.) shows that they were composed of two parts, one of which was mashed (while still in the form of unleached formation?—J. W. G.), the other being granular or crystal-outlined hematite and magnetite (and martite.—J. W. G.). The latter material fills the cracks left as a result of the mashing, perhaps occupies the place of residual silica, and welds the micaceous leaves together. Thus this granular ore was certainly de-

[39] *Idem*, p. 276.
[40] Mon. 28, p. 405.

posited after the folding. How much was introduced during the folding it is impossible to say, for this part cannot be separated from that present before the folding.

The third class of deposits which lie partly in the Negaunee and partly in the Goodrich quartzite are almost unique in their occurrence. These ores are said to be "partly recomposed" and consist in part of fragmental material which accumulated at the base of the quartzite as a basal conglomerate. Van Hise and Leith [41] reconstruct their history as follows:

> The alteration of the Negaunee formation began before upper Huronion time, when the formation had been slightly folded, eroded, and intruded by igneous rocks. Prior to upper Huronion time all the phases of the iron-bearing formation now known, except the specular hematite, had been developed, for all of them appear as pebbles in the basal conglomerate of the upper Huronion.

The absence of pebbles consisting of specular hematite in the Goodrich quartzite ores and the presence of soft ores in some of

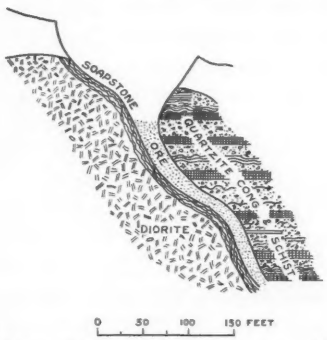

FIG. 8. National Mine, Marquette district. A replacement deposit in the Goodrich quartzite. (After Van Hise and Bayley.)

them shows that at least large portions of these "conglomerate ores" are of the second period of ore concentration. This is substantiated especially well by Fig. 8,[42] of which its authors

[41] Mon. 52, p. 278.

[42] Reproduced from Monograph 52, p. 394.

write: "On the left is soapstone grading into greenstone. Above this is hard ore, and overlying the hard ore are interstratified conglomerate, quartzite and schist. The ore is here plainly due to a replacement of the silica of the different sedimentary bands by ore, although the original conglomerate was highly ferruginous." Nor is this the only case of a replacement deposit on the Marquette range. As a matter of fact all of the Goodrich quartzite ores seem to come into this category, if we analyse the statement of Van Hise and Bayley [43] concerning them carefully:

> While a considerable percentage of the iron oxide of the ore was present as detritus, in no case does it appear that the material was rich enough for merchantable ore before secondary concentration, and often the secondary magnetite and its alteration product martite, are the predominant constituents of the ore.

Since the original iron formation contains 30 to 40 per cent. iron, any detrital material from it would contain this amount of iron. If the silica were leached and replaced in the detritus, there would result just the kind of ore described. The enormous power of the solutions is indicated by the fact that they dissolved not only chert pebbles but also quartz pebbles in these conglomerates and lined the cavities with adularia crystals.[44]

In this connection it is noteworthy that similar replacements of conglomerates have been described by P. A. Wagner [45] from the Crocodile River iron deposits in the Bushveld.

Very few deposits, if any, which extend into the Goodrich quartzite—this statement applies also to the great majority of the other ore bodies—appear to be independent of the intrusions, since they occur commonly either along dikes or on greenstone masses. The soap or paint rock between the ores and these igneous rocks, the writer considers hydrothermally altered, else how could magnetite crystals—now largely altered to martite—occur as replacements in some of the paint rock. The magnetite (or martite respectively) was clearly the last mineral to form in these alterations as stated expressly by Van Hise and Bayley.[46]

[43] Mon. 28, p. 413.
[44] Mon. 52, pp. 279 and 539.
[45] *Op. cit.*, pp. 148 and 160.
[46] Mon. 28, p. 511.

The Vermilion District.—The writer has little to add to his previous discussion on the ores of the Vermilion range, to which the reader is referred.[47] In that paper it was shown that the ores of the Ely "trough" did not undergo metamorphism after they had been concentrated, therefore were not older than post-Algoman. Doubt was expressed then that the hard Soudan ores had been metamorphosed for the reason that large cavities are frequently found in them. The mere fact that hematite ore is cemented by coarse quartz would not constitute sufficient evidence of metamorphism. At the La Rue mine on Armstrong Bay of Lake Vermilion there is a miniature Soudan mine as far as surface outcrops are concerned, but about 20 feet below the glaciated hard ore, the quartz and hematite cement give out and a "soft ore," porous like the Ely ore, is encountered. One can scarcely believe that such ore underwent metamorphism though he might have thought so by inspecting the cemented top layers.

The excellent paper by Smith and Finlay[48] long ago described and illustrated replacement deposits of jasper by massive iron ore in connection with igneous intrusions although it was thought that cold water had produced this replacement.

These authors also stated:

> Furthermore the massiveness and lack of structure in the Tower deposits show that they were formed after folding took place. For if they had been in existence before the folding, it is impossible that they alone, of all the materials of the crust in this region, should bear no mark of it.

These processes do not tell us, however, whether these ores were formed soon after the Algoman upheaval or later. The presence of outlines of feldspar crystals in the soft altered wall rocks a little distant from the ore seems to indicate that the intrusives are of relatively late age.

The Menominee District.[49]—The Vulcan iron formation is

[47] Econ. Geol., vol. 21, pp. 629–644, 1926.

[48] Smith, H. L., and Finlay, J. R., "The Geological Structure of the Western Part of the Vermilion Range, Minnesota," *Trans. A. I. M. M. E.*, vol. 25, pp. 636–644, 1895.

[49] Bayley, W. S., "The Menominee Iron-bearing District of Michigan," U. S. Geol. Surv. Mon. 46, 1904. Also U. S. Geol. Surv. Mon. 52, 1911.

divided into three members; the upper and lower are ferruginous; the middle one is slate. These three conformable members are of upper Huronian age and lie unconformably on lower Huronian dolomite (Randville) or quartzite. The thick Michigamme slate overlies the Vulcan formation conformably. The folding of these rocks is severe, and nearly everywhere the rocks dip steeply. Considerable faulting has occurred. Basic intrusives and extrusives are numerous. They are mostly post-Vulcan age. Some cut the iron formation [50] although none have been reported in ore bodies.

The mineralogical and lithological composition of the Vulcan formation is ferruginous quartzites, jaspilites, siderite, ferruginous slates and some greenalite. Van Hise and Leith [51] describe the ores as follows:

> The richer ores are usually bluish black, porous, fine-grained aggregates of crystallized hematite. These rich ores grade into leaner phases containing more or less hydrated hematite with varying amounts of quartz, serpentine, talc, clay and carbonates of calcium and magnesium. All the minerals occurring as constituents of the ores are found also as visible masses either in veins cutting the ore bodies or in vugs or pores within them. Dolomite, calcite and pyrite occur locally in excellent crystals, and serpentine as large, white almost pure masses. Talc also occurs in thick seams of almost ideal purity and chalcopyrite in small crystals associated with pyrite. The carbonates and sulphides are found near water courses and the silicates mainly in the lower portions of the ore bodies.

Of the mineral serpentine Bayley [52] writes:

> Serpentine, as has been stated, occurs almost universally in the ores, but usually in such small quantities as not to be noticeable in the hand specimen. Frequently, however, it can be detected as small gray or white particles scattered so uniformly through the ores as to give them a grayish tinge.

The ore, as commonly stated, occurs largely in "pitching

[50] Mon. 52, p. 344.

[51] Mon. 52, p. 351. These quoted paragraphs also occur in Bayley's original Monograph 46.

[52] Mon. 46, p. 389.

troughs" on impervious layers of talc schist, dolomite and quartzite.[53]

> The dolomite near the contact (with the iron formation, seen only in the mines.—J. W. G.) is usually schistose, so much so that in most places it is pure talc schist. The calcium of the dolomite has been removed and much of it has been deposited in the ore bodies as calcite, while the magnesium has remained in the talc. A surprisingly similar schist has been formed from the middle Huronian quartzite [where in contact with the ores.—J. W. G.] though on the whole it is more siliceous and less talcose. This talc schist serves as an impervious lining to many of the folds in which the ore deposits lie, and afforded better conditions for the concentration of the ore material than were afforded by the massive and shattered dolomite underlying the ore formation at many places.

Many ore bodies do not occur in such troughs, however, as is recognized by Bayley, Van Hise and Leith.[54] These bodies for the most part

> Remain near the contact of the iron-bearing formation with the underlying rocks, but at many places they leave this contact, rise into the iron-bearing beds, and thus become separated from the base of the formation by considerable thickness of jaspilites. [Hanging ore bodies.—J. W. G.] The upper surfaces are much more uneven than the lower ones. Not only are they undulatory to a greater degree, but ore projections extend upward into the overlying jaspilites. . . .

Could not the apparently greater accumulation of ore in the "troughs" be due to the more complete crushing and the thickening of the iron formation in these folds? An ore body may reach entirely across the iron formation and yet be small on a straight limb of a fold because the iron formation itself is narrow. On the other hand, where the formation is thickened due to folding, larger bodies could develop. (See also the discussion on the frequency of the occurrence of synclinal ore bodies.)

Since the ores are porous no metamorphism has occurred since the beginning of their formation. The talc-schist layers at the contacts of the iron formation and of the dolomite or quartzite respectively then would have had to form during the period of

[53] Mon. 52, p. 342.

[54] *Idem*, p. 348.

folding before the leaching of the iron formation. This, however, would not explain the quotation above that the calcium of the dolomite was removed and much of it was deposited in the ore as calcite while the magnesium remained in the talc, for such a process would have to take place during the formation of the talc and not afterwards. Or did the talc originate during the leaching of the ores? That assumption would explain the occurrence of much talc and serpentine in veins, in vugs and disseminated in the ore, which otherwise presents a most perplexing problem. The precipitation of much talc and serpentine from cold waters that dissolved such highly resistant rocks as jaspilite does not seem reasonable in the light of the experimental and field evidence that serpentine is probably the most easily soluble silicate under weathering conditions. Yet it occurs almost universally in the ore in quantities exceeding probably one per cent. and reaching several per cent. in some ores. The talc is pure white and the serpentine white or grey. Why did they not become iron stained if they originated by weathering?

The writer is of the opinion that the hot waters were high in magnesium and calcium carbonate. These carbonates either came from the magma directly or from the Randville dolomite. They attacked first the quartzite or siliceous portions of the dolomite at the contact with the iron formation. Since they were still very hot, probably above 300° C., they formed the talc "schist" at the contact. On their ascent, they oxidized and leached the iron formation and wherever of the proper composition and temperature, precipitated some of the serpentine [55] and talc.

The Cuyuna District.[56]—Less is known about the geology of the Cuyuna range district than of the other large ore districts, because there are practically no outcrops. Two main belts of iron formation (altogether about seven or eight) of a northeasterly strike have been found. The name Deerwood formation

[55] For the conditions under which a serpentine substance has been produced see: Wells, F. G., "The Hydrothermal Alteration of Serpentine," *Amer. Jour. Sci.*, vol. 18, p. 50, 1929.

[56] Harder, E. C., and Johnston, A. W., "Preliminary Report on the Geology of East Central Minnesota Including the Cuyuna Iron-ore District," Minnesota Geol. Surv., Bull. 15, 1918.

has been given to them. Whether they are of the same age is not known; they are probably upper Huronian. The iron formation is infolded in slates and schists. Many basic intrusions of Keweenawan or late upper Huronian age have been found in the iron formation and in the ore. Experience has shown that association of ore and altered basic intrusives is so common that it is considered good practice to look for ore near such igneous masses. High temperature veins have been described by Thiel [57] from the ores and their wall rocks.

The iron formation consists mainly of ferruginous cherts, iron carbonate and greenalitic phases in the northern belt, and magnetite-amphibole slates and schists in the southern. Most of the rocks dip steeply either to the north or south. The ore bodies are very irregular in shape. Some are relatively flat lying, others form steeply dipping lenses. There seems to be no indication that impervious troughs controlled ground water circulation to any extent since, as far as is known, the majority of the ore bodies extend into the iron formation down the dip. Ore is known to a depth of about 900 feet. The ore is of variable composition with soft porous hematite and limonite predominating. Martite is common in some of these ores, according to G. A. Thiel.[58] Slumping of ore due to the leaching of silica is a prominent feature in the wider ore bodies. The occurrence of manganese in these ores will not be discussed in this paper.

The Iron River, Crystal Falls, and Florence Districts.[59]—The geology of these districts is relatively little known on account of few outcrops and intense folding of the sedimentary formations, including the upper Huronian iron formation. The iron forma-

[57] Thiel, G. A., "High Temperature Manganese Veins of the Cuyuna Range," Econ. Geol., vol. 19, p. 377, 1924.

[58] Oral communication.

[59] Clements, J. M., and Smith, H. L., "The Crystal Falls Iron-bearing District of Michigan," U. S. Geol. Surv. Mon. 36, 1899.

Allen, R. C., "The Iron River Iron-bearing District of Michigan," Mich. Geol. and Biol. Surv., Publ. 3, Geol. Series 2, 1910.

Royce, Stephen, "Certain Advances in Geological Information Relative to the Lake Superior Iron Deposits," *Proc. Lake Superior Min. Inst.*, vol. 24, pp. 163–170, 1925.

tion consists chiefly of ferruginous cherts, iron carbonate, some jasper, and pyrite. It is infolded in black and pyritiferous slates. Therefore, the ore bodies are accompanied by these slates but also by "greenstones" in places. Diabase and diorite intrusions are common except in the ores from which only three or four dikes have been reported, unless some of the "greenstones" are altered intrusions. Ore bodies extend to a depth of at least 1,700 feet. Clements and Smith [60] write of the ore bodies: "Commonly the ore is completely surrounded by the chert beds, or chert and ore, forming the so-called mixed and lean ore. In such cases they form both the foot and hanging wall of the ore bodies." Ore bodies also have steeply dipping footwalls of slate. In depth the iron ore layers pass into lean cherty layers as a rule.[61]

As to the stratigraphic and structural distribution of the ore bodies of the Iron River and Crystal Falls districts Royce [62] says:

> Anticlines are not on the whole, good places to search for ore on the footwall [evidently meaning the lower horizons of the formation, J. W. G.], but anticlines have made about half a dozen known ore bodies in Iron County, located in every instance in the hanging wall of the formation. If the thickness of the formation be divided into thirds, something like two-thirds of the ore produced from the district will be found to come from the footwall one-third of the formation, mainly along synclines. Of the remainder of the ore produced from the district the greater amount will be found to have come from the hanging one-third of the iron formation, mainly in anticlinal structures. The middle of the iron formation over the bulk of the country has been of relatively minor importance, producing ore bodies which are usually small, scattered affairs, difficult to locate and not very profitable to mine.

The ores are soft hematite and limonite. They are porous and show many crystal-lined cavities.

The Mesabi District.[63]—The upper Huronian Biwabik iron

[60] *Op. cit.* p. 182.

[61] Mon. 52, p. 324.

[62] *Op. cit.*, pp. 169 and 173.

[63] Leith, C. K., "The Mesabi Iron-bearing District of Minnesota," U. S. Geol. Surv. Mon. 43, 1903. Wolff, J. F., "Ore Bodies of the Mesabi Range," *Eng. and Mining Jour.*, vol. 100, p. 96, 1915. Wolff, J. F., "Recent Geologic Developments on the Mesabi Iron Range, Minnesota," *Trans. A. I. M. M. E.*, vol. 56, pp. 142–169, 1917. Gruner, J. W., "Paragenesis of the Martite Ore Bodies and Mag-

formation overlies Pokegama quartzite and underlies Virginia slate conformably. The dip of the Biwabik formation is southward and averages about 10 degrees. Three larger faults and a sharp monocline of about 300 feet vertical component have been found.

The term taconite is applied to the rocks of the iron formation excepting the intermediate slate. Taconite is a banded ferruginous chert and greenalite rock containing some slaty phases. The most common iron mineral in the taconite is fine-grained magnetite. Next in abundance is greenalite; siderite and hematite make up the rest of the iron. Where the taconite is altered to ore, the magnetite is oxidized to martite, the silicates to limonite, and the siderite to hematite or limonite. This means that definite layers of minerals occurring as beds in the undecomposed formation alter to quite definite ore layers.

The shapes of the ore bodies are of three types: (1) the trough body, the trough being due to slumping, (2) the fissure body, and (3) the flat-lying body. The most important is the trough-shaped body. Every gradation exists between these three types.

These ore bodies apparently are so different from most of the ores of the Lake Superior region that they cannot be explained except by the weathering hypothesis. But a valid hypothesis must be able to explain the following field relations:

1. Magnetite has not weathered to *martite,* not even to a depth of one millimeter, on glaciated surfaces of the Biwabik formation in the productive portion of the district. A conspicuous example is the high taconite cliff halfway between Virginia and Eveleth. The outcrops there have been exposed for thousands of years to the weather and ground water.

2. The discovery of whole martite ore bodies to a depth of 900 feet in the ores suggests that martite is due to thermal oxidation as has been shown for many other districts of the world.[64]

netites of the Mesabi Range, Minnesota," ECON. GEOL., vol. 17, pp. 1–14, 1922. Gruner, J. W., "The Origin of Sedimentary Iron Formations," ECON. GEOL., vol. 17, pp. 407–408, 1922. Gruner, J. W., "Contributions to the Geology of the Mesabi Range, Minnesota," Minnesota Geol. Surv. Bull. 19, 1924.

[64] Wachtel, D. E., unpublished thesis, University of Minnesota.

3. The larger ore bodies of the Mesabi range are concentrated in a number of localities now marked by the sites of cities and villages. Ore bodies, of course, occur between these places, but the accumulation of ore around these centers is enormous. The reason for this bunching is not apparent from the weathering hypothesis, for the iron formation as seen in drill cores seems fairly uniform.

4. If the ground waters leached the silica, each center of ore concentration should exhibit some basin or similar structure by virtue of which it could have controlled the circulation of large amounts of water. Such structures have not been found in the Pokegama quartzite and the iron formation in spite of intensive search by many investigators. On the contrary, in the Virginia Horn (Fig. 9), the ore bodies between South Virginia and Gilbert flank a distinctly anticlinal structure which was entirely covered by iron formation in the past as shown by the small outlier of iron formation 4 miles east of Virginia (Fig. 9). One may be inclined to accept the weathering hypothesis for the ore bodies on the flanks of the anticlines. But by far the largest bodies, aggregating over 169 million tons of taxed ore, are situated on the nose of the anticline where the available drainage area covered by quartzite, slates, and graywackes could hardly have exceeded two square miles, as is shown in Fig. 9. If the whole area had still been covered by iron formation when the leaching occurred (which would have necessitated not more than 200 feet of erosion up to the present time) then the problem is still more perplexing, especially if the seventh point below is considered.

5. The spreading of the ore bodies toward the surface is less by far than one imagines when looking at open pit workings where the "benches" left on the ore for railroad tracks and safety measures, give a wrong impression. Cross sections prepared by mining companies show not only relatively little spreading in a great many places but also show taconite capping ore in the walls of many ore bodies. Since the ore bodies are of great lateral extent, the increase in horizontal area near the surface as com-

pared with the area near the bottom is relatively small. Any spreading of the ore bodies toward the surface can be explained under the hydrothermal hypothesis by the greater fracturing of the taconite nearer the surface, and the sealing by precipitated silica of the early channels of escape very close to the surface, as the solutions rose by the paths of least resistance. This explanation is the same as one used in accounting for spreading of vein deposits.

6. In many large deposits, especially east of Mountain Iron, the walls of the deposits are almost vertical and well defined. In places the writer was able to reach from high grade ore to highly magnetic unleached taconite. These walls may be 100 feet high before an appreciable offset occurs. Even on the West Mesabi range near Hibbing, it is not unusual to observe a vertical joint fissure of 30 to 40 feet in height and considerable lateral extent to separate the ore from the taconite. The taconite under these conditions may show considerable silicification by quartz veins.

7. These steep walls are not confined to the sides of the ore bodies but also occur at the ends, although to a minor extent. The ore bodies, with two exceptions, do not reach the Pokegama quartzite up the dip of the formations (as was pointed out as early as 1903 by Leith) but pinch out or stop abruptly as shown, for example, by the outlines of the pits in Fig. 9. Solid taconite is found in drilling between the edge of the quartzite and the ore bodies. This is not easily explained by the weathering hypothesis according to which the ground waters entered the iron formation on the north edge and followed some impervious bed down the dip as is shown in Fig. 10.

8. It was formerly thought that the "Intermediate slate," this persistent slate up to 20 to 30 feet thickness, had exercised much control over the circulating waters. This idea has been abandoned, for this slate (now the paint rock) occurs in the middle of practically every large ore body. There may be just as much or above as below the paint rock. In a number of places the paint rock itself has been enriched sufficiently to be mined as ore. In such cases, the bottom portion of the paint rock commonly consists of hard, dense, limonite and hematite layers and lenses.

9. The Mesabi ore bodies have no "impervious" floors or footwalls. They do not extend to the quartzite except in a few special cases as, for example, in the Biwabik and Fault pits where the quartzite has been brought up by faulting and forms the bottom of the ore in some places. The ordinarily hard quartzite consists now of sandy material. No other impervious beds or layers occur between the Intermediate slate and the quartzite, and neither of these two operated as is indicated in Fig. 10, in which a generalized cross section of a large ore body has been superimposed upon the well known diagram by Leith in which a modified artesian circulation had been postulated.

10. The axes of elongation of the ore bodies usually are more nearly parallel to the direction of the strike than to the direction of the dip.[65] This fact suggests that the solutions did not come down the dip, otherwise the leaching should have followed the dip. In the anticlinal structure of the Virginia Horn (Fig. 9), however, near Eveleth, the axes of the ore bodies follow the dip more commonly than the strike, but at Eveleth, as explained under 4, it is most difficult to see how leaching from above could have occurred. The axes of the large ore bodies at Virginia have a peculiar attitude. They occur in a flat curve which cuts off the northeast portion of the Virginia Horn as shown in Fig 9 by a heavy broken line.

11. Another impressive argument in favor of the hydrothermal hypothesis is the completeness of leaching at the bottom of the ore bodies. It is almost inconceivable that solutions saturated with silica could have descended down the dip without dropping their load and thus obstructing any possible channels for further leaching and slumping. That slow slumping occurred for considerable vertical distances and over relatively large areas in a body is proven by the fault-like breaks between the taconite and ore on both sides of the ore bodies. With their slickensided surfaces in the paint rock layers they resemble faults so closely that they were at times mistaken for them. The whole process is similar to what has been called mine subsidence due to stoping and removal of ore. If leaching had occurred first in the higher

[65] Gruner, J. W., *op. cit.*, Minn. Geol. Surv. Bull. 19, pp. 40–43.

FIG.
cate ore
Minnes

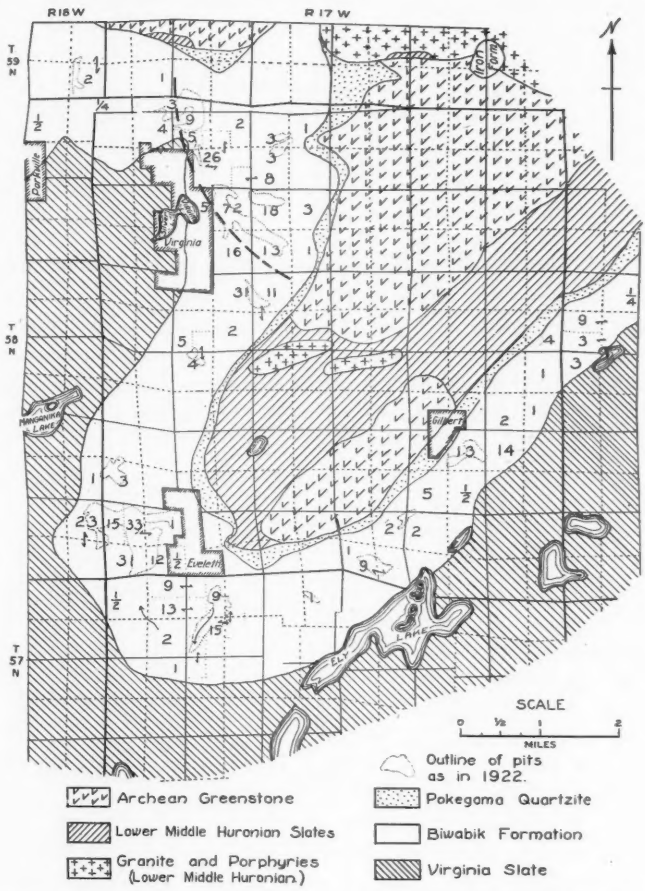

FIG. 9. The "Virginia Horn" of the Mesabi range. Numbers indicate ore in millions of tons on the various properties as recorded by the Minnesota Tax Commission.

horizons, there scarcely could have occurred slumping on such a grand scale with preservation of the bedding in the ore from wall to wall. The leaching of the taconite on the erosion surface would have left a porous loose material which would have been eroded with ease just as fast as it formed. The precipitation of silica near the surface according to the hydrothermal hypothesis, on the other hand, would have been very efficient protection for the ore bodies.

12. The concentration of manganese in coarsely crystalline quartz veins which in the process of slumping of the ore were broken into many fragments, is almost a universal occurrence on the Mesabi range. In one of these quartz veins in the Wanless mine, native copper was found. These veins are certainly of hydrothermal origin. Their relation to the ore bodies is obscure, though some of them form the walls along which slumping has taken place in the ore bodies.

13. From Keewatin westward, wash ores are encountered that contain a great deal of loose granular quartz (all cherts are really quartz now). Oxidation, however is complete. It has been said that on account of the flatter dip of the iron formation the circulation of ground water was less vigorous and more silica was left. Why then complete oxidation? In the opinion of the writer a steeper dip would scarcely accelerate circulation appreciably in a highly fractured formation without artesian conditions. Could not hot ascending waters have acted over a period of time long enough to dissolve the cement between the chert granules without dissolving them? This is suggested particularly by the gradual increase of unleached silica toward the west.

14. A seeming relationship of the ore bodies to the preglacial erosion surface has relatively little significance in the discussion of the origin of the ore for it is unlikely that the present surface coincides exactly with the pre-Cambrian surface at the time of maximum ore concentration. Weathering to ore is supposed to have kept pace with erosion. If Leith's hypothesis be accepted, according to which solutions entered at the northern margin of the iron formation, followed the bedding planes down-

ward and then rose near the edge of the Virginia slate to spill over the relatively low edge (Fig. 10), it must be postulated that the relative differences of elevation of intakes and outlets either remained the same as they are today or were larger at the time of ore concentration. This assumption cannot explain, however, why the ground water should have followed such a route, since no impervious beds existed in the formation.

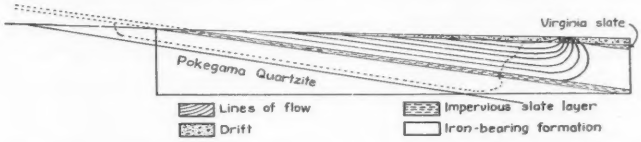

FIG. 10. Hypothetical ground water circulation in the Biwabik formation according to Leith. Generalized cross section of a large ore body (dotted line) superimposed by the present writer.

15. It is necessary to explain the probable absence of ore under the Virginia slate. The dipping of the upper Huronian formations toward the south seems to be related to the development of the great Lake Superior geosyncline and that in turn to the colossal intrusions and extrusions of Keweenawan eruptives. The Duluth gabbro overlies the Biwabik formation east of Mesabi but basic and intermediate dikes are found in a number of places in the ore and iron formations as far as 15 miles west of Mesaba.[66]

A gap of one hundred miles seems to separate these intrusions from those in the iron formation of the Cuyuna district (Fig. 4). Actually, however, fresh looking trap and dolerite dikes have been found intruded in the rocks just north of the Pokegama quartzite and in the Virginia Horn. The writer found one small dike half a mile south of the Minnewas pit at Virginia, and another one-third of a mile north of the Mountain Iron mine near the city of Mountain Iron. Other fresh basic intrusions occur north of Nashwauk.[67] Since these discoveries were made in connection with work not related to the present study, no syste-

[66] Gruner, J. W., Minn. Geol. Surv., Bull. 19, p. 7, 1924.

[67] Observed by Dr. G. A. Thiel and Dr. I. S. Allison.

matic search having been made north of the Pokegama quartzite, it is probable that more of these intrusions will be found. They are testimony that large basic intrusives are concealed under the Mesabi range and may be considered links in the chain of Keweenawan eruptives surrounding the Lake Superior geosyncline.

If it is assumed that large quantities of gases and solutions rose from these basic magmas, an assumption not any bolder than numerous other postulates of petrology, it becomes possible to explain the origin of the Mesabi ores by the new hypothesis. Since the Giants Range granite may have been an effective barrier for solutions to the north [68] the flow of the solutions and gases was confined to a narrow zone between the granite and the thinest fractured portions of the Virginia slate. In some places the slate may have been absent. This assumption would answer the question why ore bodies have not been found under Virginia slate at its present stage of erosion.

The absence of ore on the East Mesabi (the small Spring mine excepted) and Gunflint range is probably due to the overlying Duluth gabbro. It is not likely that ascending solutions could have penetrated such an enormous mass of igneous rock.

COMPARATIVE FREQUENCY OF THE OCCURRENCE OF ORE IN SYNCLINES AND ITS CAUSES.

Since so much has been written on the occurrences of ore in synclines and troughs, the reasons for their apparent frequency will be discussed. The highly folded iron formations being sedimentary and overlying older sedimentary rocks are necessarily found infolded as synclines and synclinoria in the older formations. Therefore, ore will be in these larger synclines if any exists at all. Any synclinorium cut by erosion will always have one more syncline than anticline. If the structure consists of a few folds as shown in Fig. 11 the numerical chance for the occurrence of ore in synclines is, therefore, greater than for

[68] It appears from a study of the distribution and metamorphism of the greenstone outcrops between the Pokegama quartzite and the Giants Range granite that the Mesabi range represents the southern limit of the granite batholith in the older rocks.

anticlines. In the extreme examples of only one fold no possibility exists for an anticline. Some of these extreme cases have frequently been given as illustrations.[69]

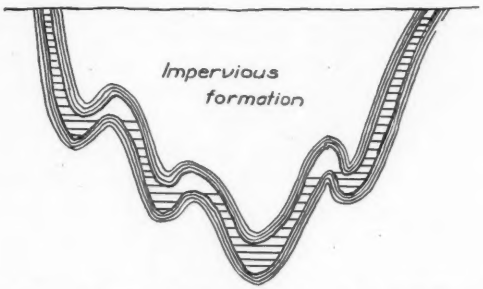

FIG. 11. Diagram of a synclinorium with four synclines and three anticlines. Shaded portions should come under the classification of synclinal structures.

Fig. 11 also illustrates another point; any ore found in the shaded portion of this hypothetical synclinorium would probably be reported as occurring in a syncline, and such would be the case. But an inspection of the figure shows that the anticlinal crests make up only a small portion of the structure. Therefore, the mathematical probability that an ore body will be in a syncline is several times greater than for an anticline.

If the iron formation is overlain by thick impervious slates, ascending solutions cannot break through the slates but must follow the highly fractured iron formation. The solutions will, however, use the shortest possible route to the surface. Since gases are liberated by the oxidation of $FeCO_3$ and the decomposition of H_2O, the tendency will be for such gases to fill the upper portions of the porous formations. The anticlines or the anticlinal portions of the drag folds should act like traps for these gases, as shown in Fig. 12. The solutions should be unable to leach these portions of the structures. These hypothetical conditions may account for some of the trough or drag fold bodies of the Menominee, Crystal Falls, and Iron River districts.

[69] For example: Chandler ore body of the Vermilion range district, Mon. 45, Figures 8 and 11, and on the Marquette range Fig. 1, in Mon. 28, Plate 29.

That synclines and descending waters alone without special conditions did not produce ore bodies can be easily demonstrated by the fact that there are many more synclines without ore than

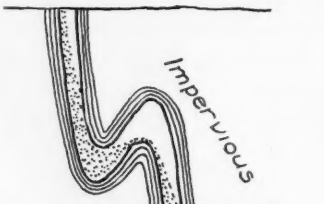

FIG. 12. Diagram illustrating course of ascending waters (dotted) in iron formation. No ore could form in anticlines on account of trapped gases.

with ore. Disregarding the ore bodies that are in structures of which intrusives are essential parts, the occurrence of synclinal ore bodies may be summarized as follows:

1. Of the seven districts (counting Crystal Falls, Iron River, and Florence as one) only three can be considered to have trough structures.

2. Of these three districts the Marquette district has few, since most of its ore bodies are clearly dependent on intrusives for footwalls or floors.

3. The remaining two districts that contain synclinal bodies also have many bodies which are not in troughs, as has been shown.

That ore bodies which occur at intersections of two intrusives or at the intersection of an intrusive mass with some slaty or similar layer (which cannot become ore on account of its com-

position) should not be included under synclinal structures in the hydrothermal hypothesis, is obvious. These ore bodies can be explained as having been produced by the direct heat of the intrusives and by the solutions which rose along the highly fractured contacts between intrusives and iron formations and along other shattered zones. How, for example, could the not uncommon case of ore bodies on both sides of the same dike be explained by the weathering hypothesis?

PROBABLE LACK OF DEEP ARTESIAN CIRCULATION.

The strongest argument for the absence of artesian conditions save to a minor extent, is the fact that there is rarely any ore found directly under an impervious bed of any kind. If artesian circulation had existed, the iron formation should have been leached more easily under impervious layers where the circulation would have been most vigorous. Without artesian conditions, however, it becomes practically impossible to account for the great depth of leaching, for the water would have been ponded in the formations. Not even with the greatest possible relief in the region at the time of ore concentration can we postulate an outlet for ground water which would have been lower than 1000 feet with respect to the rocks exposed on the present surface. There remain several thousand feet of depth of ore for which no account can be given.

A fact not mentioned before is that leaching of silica without attendant oxidation of ferrous minerals does not occur in the Lake Superior region. Waters which are capable of dissolving silica are not necessarily oxidizing. Van Hise and others, for example, think that waters high in CO_2 leached the silica but also dissolved iron carbonate. In order to account for the precipitation and oxidation of ferrous iron they postulated other waters high in oxygen "more directly" from the surface that mingled with the CO_2 waters at depth.[70] There is no reason why these two kinds of solutions should have always met. Leaching of silica should be found without oxidation of iron minerals. Ac-

[70] Mon. 28, p. 403, and Mon. 52, p. 538.

cording to the hydrothermal hypothesis, however, oxidation must result, if waters can move upward. For this ascent means that gases can move even more rapidly to a point of escape.

Given the most favorable conditions of artesian water, or even arid conditions with a very low water table throughout the whole Lake Superior region, and a long period of time, there is still one feature common to all its districts (except the Mesabi) that remains unexplained. This is, that many ore bodies do not reach the present (pre-glacial) erosion surface at any point, whether it be along the axis or the flanks of the deposits. Why should the ground water have circulated down the bedding or other controlling structures in the iron formation for considerable distances before it began to oxidize and leach?

SOURCES OF HYDROTHERMAL SOLUTIONS.

It has been shown that the whole region was subjected to tremendous volcanic activity during upper Huronian and Keweenawan time. The enormous visible intrusions and extrusions of chiefly basic character are only relatively small portions of the great masses underlying the whole Lake Superior geosyncline. That such masses must have been accompanied by the emission of large quantities of solutions and gases can scarcely be doubted. This is particularly true in the light of the evidence presented chiefly during the last two decades, especially by A. L. Day, E. T. Allen, E. S. Shepherd, and C. N. Fenner. In Fenner's latest paper [71] is the statement:

> The view that basaltic and cognate magmas are almost lacking in volatiles occurs repeatedly in geologic literature, and has become almost an axiom. They probably contain much less than the siliceous magmas, but a little evidence such as this, that their content of volatiles is not insignificant, may not be amiss.

Fenner also points out that these volatiles may escape leaving hardly a trace of their existence. The present writer ascribes this disappearance chiefly to the low silica content of the solutions.

[71] Fenner, C. N., "The Crystallization of Basalts," *Amer. Jour. Sci.*, vol. 18, p. 247, 1929.

Any carbonates that may be deposited by such solutions, either in veins or as replacement, were not formerly considered as originating from magmas. If these waters deposited their loads mainly near the surface their precipitates could easily be eroded or might not be recognized as originating from a basic magma.

If the basalts contained no large amounts of volatiles, how did the amygdaloidal cavities originate, or why was there development of volcanic glasses and zeolites? So far, the hydration of enormous masses of olivine-rich rocks to serpentine has remained unexplained. Since this seems to be a late magmatic process, from where did the serpentines receive their water?

Hulin [72] has quite recently compiled a large amount of data showing the probable presence of volatile constituents in basic magmas. There exists the belief, accepted by most geologists, that iron chlorides are common volatile constituents in these basic magmas. Van Hise and Leith [73] even go so far as to credit certain basic magmas with amounts of emanations sufficient to produce entire iron formations by chemical precipitation.

CONCLUSIONS.

Experiments show that silica from silica gel (artificial opal), chalcedony, and greenalite taconite, is soluble to an extraordinary extent in distilled water at temperatures ranging from 200° C. to 300° C. Quartz dissolves readily in water at temperatures of 250° C. and above. A basic rock like the Duluth gabbro is attacked relatively little at 300° C.

Solutions of $NaHCO_3$, $NaHCO_3 + CaCO_3$, and $NaHCO_3 + CaCO_3 + MgCO_3$ (saturated with CO_2 at room temperature) easily dissolve quartz at 300° C. but attack gabbro only very slightly.

The solubility of SiO_2 from the minerals and rocks enumerated —excepting the gabbro—is many, even hundreds, of times as great at 200° C. to 300° C. as at room temperature.

The oxidation of ferrous iron in minerals takes place in hot

[72] Hulin, C. D., "Metallization from Basic Magmas," Univ. of Calif. Publ., Bull. Dept. Geol. Sci., vol. 18, pp. 254–265, 1929.

[73] Mon. 52, pp. 516–518.

water or steam in the absence of air at temperatures as low as 160° C., provided the hydrogen given off in the decomposition of H_2O can escape.

Experiments show that siderite is oxidized to magnetite or ferric hydroxide at temperatures between 170° C. and 200° C. Above 200° C. it is oxidized to magnetite.

Magnetite is oxidized to hematite in steam or water at 258° C. and probably below this temperature. Greenalite and greenalite taconite are oxidized to a light brown substance, probably limonite, in water, beginning at 200° C. In steam, at atmospheric pressure, a darker brown is the result, and the reaction does not seem to start below 250° C.

Very small amounts, almost mere traces, of HCl, $FeCl_2$ or $FeCl_3$ promote these reactions very much. They behave almost like catalysers in this respect, that they are used over and over. With the aid of such small amounts of HCl, siderite is oxidized to ferric hydroxide at 150° C., and magnetic black oxide becomes ferric oxide at 200° C. These are probably not the minimum temperatures at which these reactions become noticeable.

Limonite is stable at 250° C. in the presence of water and steam at corresponding pressures. It changes to ferric oxide at 300° C. in the steam phase in the presence of water, but remains limonite if under water at this temperature. Further experiments are necessary, however, to confirm this behavior at 300° C.

These experimental facts lend strong support to the hypothesis that the Lake Superior hematite-limonite ores were oxidized and leached hydrothermally. It is thought that great basic Keweenawan intrusions associated with the Lake Superior geosyncline were the sources of heat and solutions necessary for the ore concentrations. The Lake Superior ores with their geologic settings have very similar counterparts in the leached ores of South Africa, especially in the Bushveld.

Since the volcanic activity in connection with the Lake Superior geosyncline began in upper Huronian time and lasted through the greater part of the Keweenawan, it is necessary to show that the great bulk of the ores was concentrated in this interval.

Practically all students of the ores believe that the concentration was completed, or at least very far advanced, at the beginning of Cambrian sedimentation since some of the ore bodies were buried under these sediments. It is not likely that ore is being concentrated at the present time in view of the fact that the iron mine waters show great similarity to water from glacial till, or other ground water.

It is more difficult to fix the time of the beginning of ore concentration. The age of all the ores that are highly porous (and most of them are of this character) is recognized as later than the last period of dynamic metamorphism and later than the basic intrusions of upper Huronian or Keweenawan age, for these intrusions are commonly the walls of the ore bodies.

There exist hard ores, however, on the Vermilion and Marquette ranges. The latter especially used to be thought pre-upper Huronian in age because they seem to consist in part of ore conglomerate at the base of the Goodrich quartzite. The writer is of the opinion that most of this detrital material was probably not ore when it was laid down as conglomerate, but derived from iron formation which later was partly leached and partly replaced by iron oxide. The relatively small amounts of micaceous hematite in the Marquette ores seem to have originated after metamorphism by the replacement of silica by magnetite and specularite in metamorphosed banded specular jasper, in which the specularite crystals were already in parallel orientation. Another argument that the hard ores are of the same age as the soft ores is their gradation into each other. This gradation has also been found in the Vermilion district. The same type of replacement of silica by specular hematite also exists there. It is highly probable that the Vermilion ores are of the same period of ore concentration.

Either upper Huronian or Keweenawan basic intrusives are found in all iron formations. In the Gogebic, Marquette, Cuyuna, and Vermilion districts they form essential parts of structures in which ore is found. The productive Mesabi range seems to be underlain by large intrusives of Keweenawan age,

for fresh diabase and trap dikes intrude the rocks just north of the Pokegama quartzite.

One of the most common arguments advanced in favor of the weathering hypothesis is the occurrence of many ore bodies in "structural troughs." An ore body occurring in a "trough" which has one or several intrusives as floor or walls was probably formed by thermal and hydrothermal action in connection with the intrusives in and below the deposit.

True synclinal troughs containing ore in the bottoms occur only in the Menominee district and its extensions (Iron River, Crystal Falls, and Florence), and to a minor extent on the Marquette range. Three reasons for the formation of these deposits can be given: (1) Gases that are released by the decomposition of H_2O and $FeCO_3$ are trapped in the anticlinal structures and prevent leaching solutions from entering them. (2) In any synclinorium, numerically more synclines occur than anticlines. (3) Much more space per unit area of a synclinorium is occupied by structures which may be classified as synclinal than anticlinal.

The impervious "soap rock" or "paint rock" of the minerals consists chiefly of talc, serpentine, chlorite, and hematite, which seem to be hydrothermal products. The extremely common occurrence of martite in the Mesabi (on a very large scale), Marquette and Cuyuna districts and its lesser abundance in the others, is a strong argument in favor of the hydrothermal hypothesis. It receives its strongest support, however, from the fact that large quantities of ore are known to occur at depths of 3,000 to 4,000 feet.

It may seem at first that the Mesabi ores do not show the important features required for a hydrothermal origin. But it was shown that the leaching solutions seem to have been ascending and not descending in practically all deposits. With an almost complete knowledge of the distribution and shape of the ore bodies on the Mesabi range, the weathering hypothesis appears inadequate to explain the origin of the ores which attain depths of 600 and 900 feet in the highly resistant magnetic taconite.

The sequence of events in the concentration of most ores would probably be as follows: Enormous basic magmas were injected into the rocks under the iron formations. Where smaller offshoots reached the iron formations the heat in the latter may have reached 400° C. or more, locally. The ferrous iron was oxidized by the gases and solutions that rose from the main magmas and probably to a small extent by ground water which happened to be in the iron formations at the time of intrusion. This oxidation, however, was possible only in places where the generated gases could easily escape. The iron formation was thoroughly disintegrated by the volume changes of the minerals oxidized, and was easily leached of its silica by the hot solutions which, on ascending, deposited their silica load at or near the surface. The deposited silica protected the underlying ores from rapid erosion. Since the solutions contained chiefly alkali and alkaline earth carbonates they had no tendency to attack vigorously rocks consisting of silicates of these metals.

In most ore bodies, especially on the Mesabi range, the temperatures probably did not exceed 300° C. in the lower portions of the formations. Even 200° C. would have sufficed, especially if small amounts of $FeCl_3$ had been in the solutions. Iron chlorides were probably instrumental in producing the replacement deposits of the Marquette and Vermilion districts.

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DISCUSSION AND COMMUNICATIONS

THE SHERRITT–GORDON COPPER–ZINC DEPOSIT, NORTHERN MANITOBA.

Sir: Certain features of my paper describing the Sherritt-Gordon ore body of northern Manitoba are discussed by Dr. J. F. Wright in the May number of ECONOMIC GEOLOGY. It is a matter of much satisfaction to me that in the main Dr. Wright and I are in agreement. Even in the chief point which he raises in his discussion I think we are of the same opinion.

If I were concerned with justifying the wording of my original paper I could point out that there is a minor synclinal structure which shows in the workings from the central shaft between the 1st and 2d levels and north of the outcrop of the ore. To introduce this fact would be merely a pointless prolonging of the discussion. I regret that Dr. Wright has not happened to see the annual report of the Sherritt-Gordon Mines for the year ending October 1st, 1929. My description of the geological conditions at the mine is as follows:

> The regional structure is that of a major anticline to the south of Sherritt-Gordon. At Sherritt-Gordon the beds have been dragged into a sharp fold, the axis of which plunges at an angle of between 20° and 25° nearly due east. The intersection of the surface with this inclined fold results in the apparently warped plane of the vein. The area near the west shaft is on the under side of the part of the beds pulled over to the south. Along the vein to the southeast the dip steepens as the surface cuts the upper part of the drag at higher and higher levels. At the east shaft the dip is to the southwest, or opposite to that at the west shaft since the surface is, at that point, on the upper surface of the over-dragged portion of the fold. On the major fold minor drags have been superimposed.

The anticline referred to by Dr. Wright is the "sharp fold" in my description. Without diagrams it is extremely difficult to make clear closely folded structures of this kind. The terms major and minor must evidently be relative. So far as the Sherritt-Gordon body is now known there is a syncline that may be the

bottom of a drag fold which in turn is superimposed on the southwest limb of a larger drag fold on the northeast limb of what both Dr. Wright and I have called a major anticline. The major anticline is south of the outcrop of the vein, the other structures are north of it. I think I should in justice add that the structure as described above is essentially the structure as interpreted by Mr. E. L. Brown, Superintendent of the Sherritt-Gordon, before either Dr. Wright or I visited the property.

In discussing the mineralogy of the deposit, Wright remarks that I evidently consider all the scapolite to be formed by reactions between the vein solutions and wall rocks. Only one crystal of scapolite has yet been reported from this district. I found that in ore from the east shaft. In my own microscopic examination none has been recognized in the gneisses, and I know of no mention of it by others. Wright suggests that scapolite may have formed by the recrystallization of the limy beds in a way similar to the formation of the other minerals of the gneisses, and then the inclusion of the crystal in the ore in which it was completely embedded. The apparent absence of scapolite in the gneiss places the burden of proof on Dr. Wright. Further, however, there are the following facts to be considered. The scapolite crystal is well formed with smooth faces and sharp angles. It is by far the most nearly perfect crystal of any kind that I have found associated with the sulphides. Is it likely that a scapolite crystal formed by recrystallization of the sediments and then included in the ore would have resisted attack by solutions sufficiently active to have corroded the quartz grains, and have formed, as Wright admits, "a narrow fringe of deep green chloritic material along the borders of some grains of amphibole"?

I have in mind that Winchell states that scapolite is not stable under anamorphic conditions. I have not facilities to search the literature on this point at this time. It seems at least doubtful if chlorine would be retained through the breaking down of the original sediments and reconstitution of the altered material into the gneisses except as a constituent with typical igneous affinities, such as apatite.

The occurrence of scapolite in the series at Reindeer Lake has no bearing on the discussion. I am acquainted with the rocks at only two places on Reindeer Lake, the southern end and Paskwachi Bay. The intrusion by granite and pegmatite is as intimate, if not more intimate in those localities than it is at Sherritt-Gordon. There is, therefore, at least as great likelihood of contact-metamorphic minerals. Dr. Stockwell, as I remember, describes the scapolite rock as probably formed by the metamorphism of an original impure limestone. I cannot recall that he uses the word contact, but I did not gather from his description that he considered that the scapolite rock is merely recrystallized impure limestone. No conditions could be more perfect for the formation of contact-metamorphic minerals. Bodies of sulphides are not necessarily present with all contact-metamorphic mineral occurrences.

Much of the garnet is undoubtedly the result of recrystallization of original sedimentary material, and the similarity in composition of garnet of that origin is so striking that it has been used in a recent paper as an argument in favor of the sedimentary origin of the gneisses. But Dr. Wright has not recognized or, at any rate, has not mentioned the fact that there are garnets of more than one kind. On the Wiltsey Henderson claims, northwest of the Sherritt-Gordon proper, garnet occurs in masses of considerable size and purity. Specimens of this garnet have been analyzed and although it is, like the disseminated garnet in the gneiss, the variety almandine, it contains decidedly different proportions of calcium, magnesium and ferrous iron. This is noteworthy in view of the constancy of the garnet in gneisses from widely separated localities. The garnet on the Wiltsey Henderson claims is probably contact-metamorphic in character. It is earlier than the chalcopyrite mineralization but is later than most, if not all, of the pyrrhotite.

The latter part of Dr. Wright's contribution is a restatement of the facts of the mineral relations not differing from mine and requiring no further discussion.

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THE GENESIS OF LODESTONE.

Sir: Two recent articles have appeared in ECONOMIC GEOLOGY concerning the origin of lodestone, one by Newhouse [1] and a later one by Gruner.[2] Newhouse believes that lodestone is due to a magnetic brownish ferric oxide of iron, similar in form and properties to magnetite but brownish in color under the microscope. Gruner discusses the occurrence of this magnetic brownish magnetite and concludes that lodestone is not due to this mineral but that the association, if it exists at all, is accidental. He did not find this brownish magnetite associated with the pieces of polished lodestone which he examined. Gruner offers no theory of origin of his own, unless his statement, "that lodestone is relatively more common on the surface and at the extremities of a magnetite deposit is not surprising. A crowding of the magnetic lines of force of the earth's field would be expected in those places," can be taken to mean that he believes lodestone to be due to the force of the earth's magnetic field.

Origin.—The writer believes that lodestone is due to lightning striking outcrops of magnetite or striking the ground very close to such outcrops. Usually when lightning strikes the ground or an outcrop it splits and runs along the surface for a distance. This is especially true when it strikes outcrops. The tongue of lightning running over an outcrop sets up a strong magnetic field, and when this takes place on a magnetite deposit it would have an effect analogous to placing the magnetite within the field of a strong electro-magnet.

A few years ago the writer was within a few feet of an outcrop of ferruginous sandstone when it was struck by a small bolt of lightning. The lightning split and ran down the two sides of the outcrop for a distance of some ten feet. The width of the two forks was between an inch and a half and two inches. The magnetic field set up by this lightning on the outcrop, although brief in duration, must have been very great.

What is Lodestone?—To the best of the writer's knowledge no

[1] ECON. GEOL., vol. 24, pp. 62–67.
[2] ECON. GEOL., vol. 24, pp. 771–775.

defining limits between lodestone and magnetic magnetite have been made. There is obviously some point at which lodestone loses its identity as such and becomes magnetic magnetite. This gradation from lodestone to magnetite is gradual and an arbitrary limit must be set to mark the one from the other.

Dana [3] says of lodestone, "the property of polarity which distinguishes the lodestone is exceptional." However a great amount of the magnetite or other minerals which show polarity is certainly not lodestone. Most magnetite will show enough polarity to affect a compass needle. The writer has found pure specularite with a decided polarity but it was certainly not lodestone. It is here suggested that magnetite with a magnetic strength of, or greater than, 250 magnetic lines per square centimeter, or a lifting power of 2.5 grams per square centimeter, be considered lodestone and all magnetite showing polarity of less magnetic strength than the above be considered as magnetic magnetite.

The material to which the term lodestone was first applied was of far greater magnetic strength than this. According to old legends, lodestone was first noticed by herdsmen in Magnesia when they found that the iron ferrules of their staffs adhered to a heavy black rock. The lodestone used by an early experimenter in electricity and magnetism was strong enough to support small metal images of human beings. Lodestone should be strong enough to orient itself in the earth's magnetic field if properly suspended, if it is to have the property implied by its name. In this paper, magnetite of the above strength is considered lodestone and magnetite below this magnetic strength is considered as magnetic magnetite.

Occurrence.—Lodestone occurs, as a rule, on or just below the surface of the earth. On the surface it is found occurring in two forms: (1), as boulders or pieces of magnetite outcrop in the soil around the outcrop or as part of till or rubble; (2), as a part of the outcrop itself, either exposed on the surface or lying just below the surface.

[3] System of Mineralogy, Sixth Ed., p. 226.

Since magnetite, either weathered or fresh, is quite susceptible to magnetic influence, it is reasonable to suppose that when a surface area of an outcrop is magnetized, the magnetic influence will be extended to surrounding areas in diminishing strength ratio. The area of this influence will obviously depend upon the initial magnetism. However, the writer has never observed lodestone as an integral part of a magnetite deposit over fifty feet below the surface. It would appear that the strength of surface lodestone fails at a comparatively shallow depth and lodestone will be limited to the surface of a deposit except in very exceptional cases where the magnetism has been very great.

As stated by Dana, lodestone is exceptional or rare. It is especially rare when the amount of known magnetite is considered. Outcrops of magnetite are comparatively common and the amount of magnetite in known outcrops and underground areas is large. There are several large areas of magnetite which instantly come to mind for every well known locality of lodestone.

In a magnetite area where lodestone occurs it has been the writer's experience that the occurrence is erratic. If any generalization can be drawn it is that the lodestone is most common about the higher points of the outcrop or the more exposed areas. There is certainly no segregation of lodestone at the ends of the ore body; if anything, the opposite is true.

Artificial Lodestone.—Artificial lodestone can be made by placing magnetite within the magnetic field of either a permanent magnet or an electro-magnet. The stronger the magnetic field the greater will be the magnetism induced in the magnetite. There is apparently no difference in the quantity of magnetism that fresh magnetite takes, from that of weathered magnetite, except that the weathered magnetite is more apt to be pure than the fresh piece. The fresh magnetite ore will contain a certain amount of gangue which would be weathered away in the surface ore. This gangue might tend to separate the lodestone and break the unity of the magnetic mass.

Both weathered (niggerhead ore) and fresh magnetite were placed in the same magnetic field of an electro-magnetic separator

and it was found that there was apparently no difference in the quantity of magnetism that was taken by both pieces or in the remanence of the different ores. One piece has hung for over a year with as many small finishing nails as it would support when it was magnetized and, as far as known, has not dropped a single nail.

Other Theories of Origin.—As before stated, Newhouse advances the theory that lodestone is due to the presence of a "brownish oxidized magnetite" which is very susceptible to magnetic influence. The writer has examined many pieces of polished magnetite, most of them from localities from which Dr. Newhouse has collected material, and finds it difficult to recognize this brown magnetite. If this brown magnetite is as common as one is led to believe by the papers of Newhouse and Callahan, one would certainly expect to find lodestone more abundant than it is. As iron is oxidized to magnetite it loses some of its magnetic potentialities. Likewise, when magnetite is altered to hematite by oxidation it loses most of its magnetic potentialities. It is rather difficult to understand why the peak of high magnetic susceptibility for iron oxide should fall between magnetite and hematite, in the zone where iron oxide loses most of its magnetic susceptibility.

If lodestone is due to this oxide of magnetite there is no reason why it should not appear at any point in a magnetite deposit above the ground water level and this ground water level would be the only limiting factor of its vertical extent. The occurrence of lodestone does not bear out this conclusion. One does not look for lodestone in the stopes of a mine but among the boulders on the surface. While it is true that the surface is the place of greatest oxidation one would conclude that, since this brown magnetic magnetite is apparently the first step in the oxidation of magnetite, it should take place anywhere in the zone of oxidation.

The association suggested by Newhouse, of limonite and lodestone, is significant only in so far as limonite is a common mineral of surface alteration and a common associate of surface minerals. There can certainly be no inter-relation of limonite

and lodestone, as pointed out by Gruner, or there would not be the great difference in the frequency of occurrence of the two.

Mr. Newhouse states that, "the magnetic field is usually strongest at the ends of the orebody," and Mr. Gruner makes the statement "that lodestone is relatively more common on the surface and at the extremities of a magnetite deposit is not surprising. A crowding of the magnetic lines of force of the earth's field would be expected in those places." It is difficult to understand why there would be magnetostriction at the ends of a long more or less tabular deposit of magnetite striking east and west and also in one striking north and south. This condition might exist in the latter case, it is granted. An iron rod with the longer dimension lying across a weak magnetic field does not become polarized. Why should a magnetite deposit striking east and west across the magnetic field of the earth acquire polarity strong enough to produce lodestone and have magnetostriction at the ends of the deposit? Yet, to cite one example, lodestone is fairly common at Cornwall, Pennsylvania, an ore body with a general east-west strike.

Summary.—Lightning striking outcrops of magnetite ore is suggested as a theory for the origin of lodestone.

Lodestone is defined as magnetite with 250 magnetic lines per square centimeter or a lifting power of 2.5 grams per square centimeter, or above.

Lodestone is limited, as a rule, to the surface or within a few feet of the surface.

Lodestone does not occur most frequently at the ends of a deposit but as a rule at the higher or more exposed areas.

Lodestone is a comparatively rare mineral.

The theory, proposed by Newhouse, that lodestone is due to a brownish oxidized magnetite does not meet all the conditions under which it occurs naturally, and is formed artificially. The theory that it is formed by the magnetic field of the earth is equally inadequate.

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REVIEWS

Oil Fields in the United States. By WALTER A. VER WIEBE. Pp. vii + 629, figs. 230. McGraw-Hill Book Company, New York, 1930. Price $6.00.

The petroliferous provinces in the United States are classified in this text according to tectonic units. Although at first glance, it appears as if the idea were radically different from the geographical classification formerly in vogue, there is really but one essential difference, namely that the great area formerly referred to as the Mid-continent province is subdivided into a number of provinces which include the Western Coal Basin, the Ouachita-Amarillo Mountain, the Bend Arch, and the West Texas Basin provinces. The oil fields of Arkansas, Louisiana and south and east Texas are placed in the Gulf Embayment province along with the salt dome fields.

The text differs from the usual book on petroleum in that the author does not discuss the origin of oil, theories of migration, accumulation, etc., except insofar as some such discussion is required in connection with the fields of any individual area.

The book suffers somewhat from what might be termed improper advertising. It does not, as is claimed, describe every oil field in the United States, and if the author had attempted this task, he would have made the book much less valuable than it is. There is also evidence of a certain amount of lack of care in assembling the figures and tables. To consider a few examples: Near the beginning of page 42 the author refers to "the following table" and the table appears on page 44. Towards the end of page 42, a reference to a figure is misplaced so that the figure referred to has practically nothing to do with the subject matter immediately preceding the reference. Again on page 46, reference is made to certain wells which have reached the white Medina, and the reader is again referred to this table on page 44 which mentions the grey Medina but not the white Medina. On page 55, the stratigraphy of West Virginia from the Cambrian to the Permian is mentioned, and the reader is informed that the information is gathered into a single columnar section. The section, however, begins with the Catskill and ends with the Monongahela series. On page 59, in discussing the Appalachian province, the author points out that a "glance at the map (Fig. 11) will show that there is more than a fortuitous parallelism between the long oil producing zones and the major folds." Since figure 11 is a portion of the U. S. G. S.

map showing the distribution of oil and gas fields in Pennsylvania, it gives absolutely no clue to the structure of the region except the arrangement of the oil fields. Again on page 85 we find the following sentence referring to the top of the Niagara limestone in Kentucky: "This limestone does not produce oil or gas in the eastern part of the state (see Fig. 41, p. 113)." On turning to page 113 we find a diagrammatic section from east to west across the Cincinnati anticline in southern Kentucky.

There are other examples of this sort of thing, together with occasional references to figures which are not on the page to which the reader is referred, which do not show what it is claimed that they do show, or which are made to refer to two or more different things. This confusion is not important to the reader who has a fair general knowledge of the subject, but might prove disconcerting to one who is using the text as an introduction to American oil geology.

The author has included in the text a large number of stratigraphic sections. Most of these are very good, but there seems to be no uniformity in their presentation. In many of the sections the oil-bearing horizons are starred. In others a separate table of oil and gas horizons is given. The same lack of uniformity appears in many places in the text. In some places certain formation names are italicized and others are not, while in other places there are no italics. Just why these differences appear is not clear.

The reviewer has a much more favorable opinion of the book itself than of its make-up. The tectonic classification appears to be a very logical one and the way in which each province is described is equally logical. The author discusses first the distribution of fields in each area followed by the tectonics of the area and its stratigraphy with a somewhat detailed account of the producing horizons and the relation of production to structure. In some cases a number of fields in a single area are described, and in other cases the author contents himself with a description of a single field. Following each chapter is a brief bibliography which includes the more important recent articles dealing with the area under consideration. Here, again, the author's choice has been judicious.

In a text of this kind where correlations are of great importance, particularly in the case of formations which extend across more than one tectonic area, a good index is essential; yet we find, to take a single example, that on page 138 in a paragraph of six lines reference is made to one structure and four oil sands, and in the next paragraph of the same length, to three pools and one fault line, and none of these names appear in the index. The counties in which the pools are located are also mentioned in the text but not in the index.

It is to be regretted that a text which presents the essential facts of

American oil field stratigraphy in a very logical way, and with a completeness which could not be surpassed in a book of this size, should be marred by the weaknesses to which the reviewer has referred. In spite of these defects the author presents his subject extremely well. The reader is not forced to wade through the usual number of chapters of generalizations, many of which cannot be generally applied. There is need for a book of this kind and the reviewer feels that he can recommend it highly to all interested in the geology of the oil fields of the United States.

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Tables for the Determination of Minerals by Means of their Physical Properties, Occurrences, and Associates. By E. H. KRAUS and W. F. HUNT. 2d Ed. Pp. ix + 266. McGraw-Hill Book Co., New York, 1930. Price, $3.00.

The second edition of Kraus aand Hunt's Tables differs little from the earlier edition. The tables contain the names of a few more minerals and varieties; the Introduction has been enlarged by references to several additional physical properties, and there is a new table in which the arrangement of the minerals is according to specific gravity.

The book is so favorably known that a more detailed description of its contents is unnecessary.

W. S. BAYLEY.

The Underground Geology of the Western Part of the Tonopah Mining District, Nevada. By T. B. NOLAN. Pp. 35, fig. 1, map. Univ. of Nevada Bull., vol. 24, no. 4. Reno, Nev., Aug., 1930.

In this preliminary bulletin the author succinctly presents new views regarding the geology of this famous silver district. He differs entirely from Spurr in that he considers most of the volcanic rocks to be extrusive and not intrusive and that the ores occur in several formations rather than being confined to one. He shows that the formations have been tilted to form a monocline reaching dips of 60° and that these folded beds are cut by a remarkable compound fault along which the rocks on the upper side have moved eastward about 1500 feet. Sympathetic faults have formed with it, and the faults have controlled the localization of the ore. One infers that the metallization is confined to a single period and not to the number of periods postulated by Spurr. This refreshingly new conception is supported by careful observations and logic and may be important in the economic life of the district.

ALAN BATEMAN.

Petroleum: Facts and Figures. (Third edition.) American Petroleum Institute. Pp. 232. 1930.

The third edition of this valuable reference book is somewhat smaller than its predecessor which was issued in 1929. All of the statistical tables appear to be retained, however, and the book provides the most complete and up-to-date figures on all phases of the oil industry available at the present time.

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Conservation of Our Natural Resources. Revision of Van Hise's book under editorship of LOOMIS HAVEMEYER, by G. A. ROUSH, F. H. NEWELL, H. S. GRAVES, G. S. WEHRWEIN, P. G. REDINGTON, and E. HIGGINS, with foreword by JOHN HAYS HAMMOND. Pp. 551, figs. 91. Macmillan, New York, 1930.

The revision of this well known book has been so drastic that it is almost completely rewritten. Modern viewpoints have been contributed by specialists and the statistical matter has been brought up to date. The individual chapters give an idea of its contents: Introduction (Havemeyer); Mineral Resources (Roush); Water (Newell); Forests (Graves); The Land (Wehrwein); Wild Life (Redington, Higgins); Conservation and Mankind (Havemeyer).

In the revision, the part on mineral resources has been considerably shortened and the chapter on wild life has been added. The parts on land and water are comprehensive and particularly interesting. The book brings together much valuable material on natural resources and through careful editorship has been made highly readable.

A German-English Technical and Scientific Dictionary. By A. WEBEL. Pp. 887. E. P. Dutton & Co., New York, 1930. Price, $10.50.

Geologists and other scientists who read scientific German realize the difficulty oftentimes in finding in ordinary dictionaries suitable translations of German technical words. This volume is to supply such needs. It gives dependable translations of some 75,000 words used in the fields of chemistry, botany, engineering, mineralogy, and industrial technology. At the end there are 142 pages of botanical terms with corresponding English and German names. Latin type faces are used throughout. The book represents an enormous amount of work and should be invaluable to scientists and industrialists who wish for a dependable reference of ready translations of German technical words.

BOOKS RECEIVED

Oil and Gas in Oklahoma. Bulletins 40–PP to 40–XX, Okla. Geol. Survey, Norman, Okla., May, 1930 (July). A series of bulletins giving detailed discussions of geology and of oil and gas in the following counties: Jefferson, by J. R. Bunn; Cherokee and Adair, by I. H. Cram; Tulsa, by W. F. Cloud; Oklahoma, by A. Travis; Pottawatomie, by T. E. Weirick; Blaine, Dewey, Custer, and Roger Mills, by R. L. Six; Lincoln, by D. Radler; Beaver, Texas, and Cimarron, by R. L. Six; Hughes, by J. P. Boyle.

Water Supplies for Cattle along the Kondoa Irangi-Handeni Route. By F. B. WADE. Pp. 24, pls. 6. Geol. Surv. Tanganyika Territory, Short Paper No. 5, 1930.

Effect of Vacuum on Oil Wells. By B. E. LINDSLY AND W. B. BERWALD. Pp. vi + 133, figs. 63. U. S. Bur. of Mines Bull. 322, 1930. In general, pressure has advantages over vacuum in oil production except in town lot operations.

Geology and Ore Deposits of the Wood River Region, Idaho. By J. P. UMPLEBY, L. G. WESTGATE, AND C. P. ROSS, with a description of the Minnie Moore and nearby mines by D. F. HEWETT. Pp. 250, pls. 33, figs. 20. U. S. Geol. Surv. Bull. 814, Washington, 1930. Price, 90 cts. Detailed discussions of rocks, structure, history, and economic geology. Study of lode and contact-metamorphic deposits of silver-lead and gold. Excellent mine maps and sketches. Valuable contribution.

Gas-Lift Method of Flowing Oil Wells (California Practice). By H. C. MILLER. Pp. 118, figs. 45. U. S. Bur. of Mines Bull. 323, 1930. Details in use and results of various gas lift methods.

The Mineral Industry of New Jersey for 1928. Pp. 29. Dept. of Cons. and Devel. of New Jersey, Geol. Ser. Bull. 34, 1930.

Mineral Resources of Brazil (in English). By E. P. de Oliviera. Pp. 28, figs. 12, maps 2. Serv. Geol. e Min. do Brasil. Rio de Janeiro, 1930. Summaries of occurrence and brief descriptions of minerals.

Report on Molybdenite Deposit at Azegour, Morocco. By L. DUPARC. Pp. 31, colored maps and sections. Commercial report privately published by Le Molybdène, Paris, April, 1930. An excellent brief summary of geology and of molybdenum deposits.

Zinc Smelting from a Chemical and Thermodynamic Viewpoint. By C. G. MAIER. Pp. 91, figs. 19. U. S. Bureau of Mines Bull. 324, 1930. Price, 20 cts.

Geology and Mineral Resources of Northwestern Alaska. By P. S. SMITH AND J. B. MERTIE, JR. Pp. 351, pl. 34, figs. 22, topog. and geol. maps in pocket. U. S. Geol. Surv. Bull. 815, 1930 (Sept.). Price, $1.00. A monographic treatment of results of several seasons

of work in the north; general descriptions, descriptive geology, petroleum, coal, gold placers, and miscellaneous economic geology.

The Surface History of the Earth. By JOHN JOLY. 2d edition. Pp. 211, figs. 11, map. Oxford Press, 1930. Price, $3.50. A revision of this well written and interesting book, partly amended to meet the drastic criticisms leveled at it. The hypothesis, now termed Theory of Thermal Cycles, to account for mountain building and revolutions by radioactivity, is essentially unchanged.

Gällivare Malmfält. By PER GEIJER. With Summary of the Geology of the Gällivare Iron Ore Field, 9 pp., in English. Pp. 115, figs. 71, maps 4. Sver. Geol. Undersökn. Ser. Ca, No. 22. Stockholm, 1930. Price, 10 kr. An exhaustive treatise on the petrology and origin of these large and classical iron ore deposits. Considered to be the metamorphic equivalent of the Kiruna type.

Geology and Ore Deposits of the Boulder Belt, Kalgoorlie, Australia. By F. L. STILLWELL. Pp. 110, pls. 17, figs. 8, separate book of 13 large mine maps. West Australia Geol. Surv. Bull. 94. Perth, 1929 (July, 1930). Detailed petrology; rock alteration; relation of ores to rocks; discussion of gold deposits. Valuable work. Mine maps on large scale particularly interesting.

Geological Survey of Great Britain and Museum of Practical Geology; Summary of Progress for 1929: Part I. Pp. 100+ viii, figs. 7. H. M. Stationery Office, London, 1930. Price, 55 cts. plus postage.

Ordnance Survey of Great Britain; Report of Progress, for year ending March 31, 1930. Pp. 22, diagrams 6. H. M. Stationery Office, London, 1930. Price, $1.20 plus postage.

Les Mines d'Or de Gondo. By M. GYSIN. Pp. 123, figs. 61, map. Geol. de la Suisse, Ser. Geotech. XV., Berne, 1930. Price, 15 fr. Occurrences and origin of gold veins and their exploitation. (In French.)

Erzvorkommnisse des Bündner Oberlandes und ihre Begleitgesteine. By C. FRIEDLAENDER. Pp. 70, figs. 8, pls. 3. Geol. der Schweiz, Geotech. Ser. XVI, Heft 1. Bern, 1930. Price, 8 fr. Discussion of rocks, and occurrences and origin of magnetite-copper deposits of Puntaiglas; pyrrhotite of Darvela; pyrite-tourmaline deposits; zinc-lead-antimony deposits of Alp Nadèls; zinc-lead-copper deposits of Ruis. (In German.)

The Gypsum Industry of Canada. By L. H. COLE. Pp. 164, pls. 20, figs. 23, map. Canada Dept. of Mines No. 714. Ottawa, 1930. Price, 30 cts. Occurrences and production in each province; technology and uses; the industry and statistics.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

H. DeWitt Smith, of the Newmont Mining Corporation, is at present in London.

Hans Schneiderhöhn of Freiburg and Paul Ramdohr of Aachen, Germany, are preparing together a new book on the examination of ores under the microscope.

William Burns, former manager of the N'Changa Mines in Northern Rhodesia, is now living at 21 Follen Street, Cambridge, Mass.

William F. Prouty, professor of economic geology in the University of North Carolina, was a recent visitor in New Haven, Conn.

W. E. Wrather, of Dallas, Texas, has returned home after a prolonged trip in Europe.

D. M. Wallace has resigned his position with the Geo. F. Gatty Oil Company to take up general consulting work.

E. B. Hopkins, consulting geologist of 25 Broadway, New York, will spend the winter in San Antonio, Texas.

James A. Tong, after completing work for a Ph.D. degree at Johns Hopkins University, has taken the position of chief geologist for the Standard Oil Company of New York in Venezuela.

Guy C. Riddell is in Russia as consultant to the State Non-Ferrous Metal Trust and adviser to the Soviet Department of Labor on Russian and Siberian questions.

Van H. Manning, vice-president and director of research and engineering for the Petroleum Research Corporation, has resigned to take up consulting practice in the petroleum industry at Forest Hills, Long Island, N. Y.

W. W. Mein has returned to San Francisco after some time spent in Africa.

Lawrence M. Gould, University of Michigan, geologist with the Byrd Antarctic Expedition, lectured before the National Geographic Society at Washington, D. C., on November 14, on the subject "With Byrd to the Bottom of the World." The next day he gave an informal talk about Antarctic geology to geologists of the Geological Survey.

W. H. Whittier, of Berkeley, California, for ten years connected with the Royal Dutch Shell Company, has resigned to study for a Ph.D. degree in the University of California.

Recent drilling at the Chino Mine, New Mexico, has added 30 million tons of ore to the reserves.

The Salyer Consolidated Mines Company have started what is said to be the largest and most important placer mining development in the history of California and possibly of the world, when water was turned on their properties in Trinity and Humboldt Counties.

The Washington Academy of Sciences was addressed on November 20 by Adolph H. Schultz of the Johns Hopkins Medical School, on "Man's Place among the Primates," as a part of the series on Origin and Evolution.

The Shreveport Geological Society has elected the following officers for the year: President, S. C. Stathers, Standard Oil Company; vice-president, C. L. Moody, Ohio Oil Company; secretary-treasurer, G. W. Schneider, Texas Company.

The 16th annual meeting of the American Association of Petroleum Geologists will be held at San Antonio, Texas, March 19–21, 1931.

The Geological Society of America will hold its 43d annual meeting at Toronto, Canada, December 29–31, under the auspices of the University of Toronto. The address of the retiring president, R. A. F. Penrose, Jr., will be delivered at the Royal York Hotel on December 29 at 8:00 P.M., on the subject "Geology as an Agent in Human Welfare." This will be followed by a complimentary smoker in the Royal York Hotel. The Dinner will be held on December 30. The associated societies will meet concurrently. The Society of Economic Geologists will meet in the Mining Building.

Cassius A. Fisher, well known petroleum geologist of Denver, Colorado, a graduate of Yale, past member of the U. S. Geological Survey, and Treasurer of the Society of Economic Geologists, died at Denver on November 4.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.

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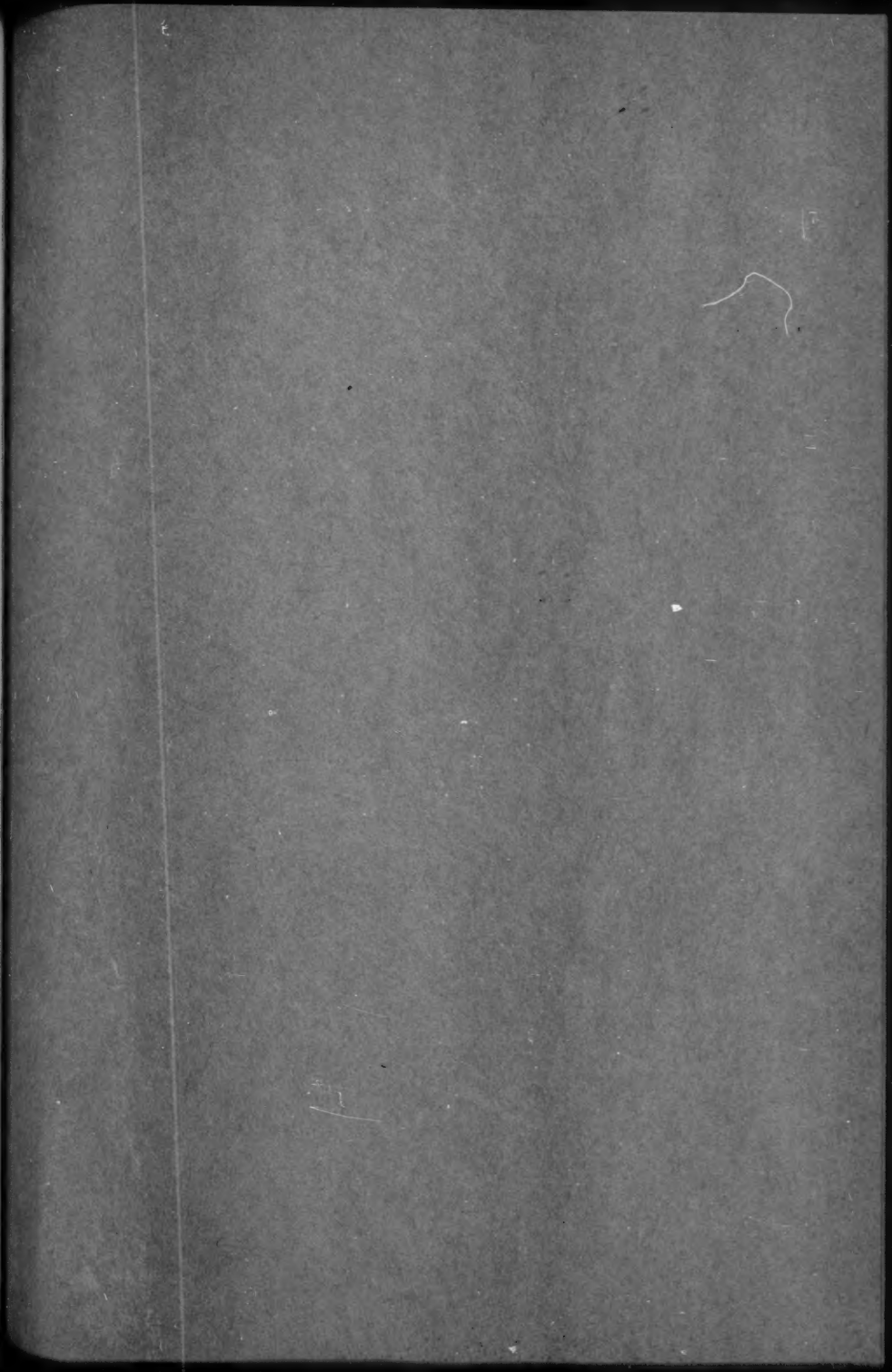

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